Near-real-time Satellite Cloud Products For Icing Detection And Aviation Weather Over The USA

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OBJECTIVES

• Develop a satellite-based icing detection methodology that can be applied operationally with results provided in a timely manner as part of an integrated icing product for the aviation community

• Use satellite data to provide near-real time cloud-top & base altitudes for aviation weather applications

OUTLINE

- DESCRIPTION OF METHODOLOGY AND CLOUD PRODUCTS
- RELATING AIRCRAFT ICING TO SATELLITE CLOUD PARAMETERS
- SATELLITE FIELD SUPPORT
- DEMONSTRATION OF PROTOTYPE PRODUCT

APPROACH

- **Use cloud properties currently being derived from satellite data at various time and space scales and relate them to aircraft icing**

-Developed & applied algorithms to various satellite (GOES, AVHRR, etc.) data for field programs for climate research

- Currently deriving global cloud and radiation parameters from EOS sensors for global change studies as part of the Clouds and Earth's Radiant Energy System (CERES) Experiment **post processing**

- Applying similar algorithms to 4-km GOES data to derive cloud and radiation parameters for DOE ARM program over SGP, for NASA CRYSTAL(FL), Icing (Midwest) **running experimentally in R/T**

PIXEL-LEVEL CLOUD PROPERTIES

EFFECTIVE RADIATING TEMP	Tc
EFFECTIVE HEIGHT, PRESSURE	Zc, pc
TOP PRESSURE, HEIGHT	p_t, z_t
THICKNESS	h
EMISSIVITY	□
PHASE (water or ice; 1 or 2)	P
WATER DROPLET EFFECTIVE RADIUS	re
OPTICAL DEPTH	□
LIQUID WATER PATH	LWP
ICE EFFECTIVE DIAMETER	De
ICE WATER PATH	IWP

Blue indicates utility for icing

ICING

ICING CONDITIONS ARE DETERMINED BY CLOUD

- liquid water content, *LWC* — **positive w/ intensity**
- temperature, *T(z)* — **negative w/ intensity**
- droplet size distribution, *N*(*r*) — ***r* positive w/ intensity**

SATELLITE REMOTE SENSING CAN DETERMINE CLOUD

- optical depth, □
- effective droplet size, *re*
- liquid water path, *LWP*
- cloud top temperature, *Tc*
- thickness, *h*

IN CERTAIN CIRCUMSTANCES

CLOUD PRODUCTS VS. ICING PARAMETERS

- $LWP = LWC * h$

- re = f[$N(r)$]

- Tc & h can yield depth of freezing layer

- z_t is top of icing layer

- ceiling = $z_t - h$

IN MANY CASES, SATELLITE REMOTE SENSING
SHOULD PROVIDE ICING INFORMATION

DATA

- **GOES-8 IMAGER (4KM RESOLUTION) 75° W**

Visible	**(0.63 μm; ch.1)**
Solar Infrared	**(3.9 μm; ch.2)**
IR Window	**(10.8 μm; ch.4)**
Split Window	**(12.0 μm; ch.5) (G-12: 13.3 μm)**

Visible Channel Calibrated Following Minnis et al. 2002

- **Rapid Update Cycle (RUC) 20 km x 20 km hourly analyses**

  - surface air temperature => skin temperature
  - temperature & moisture profiles => absorption correction, heights

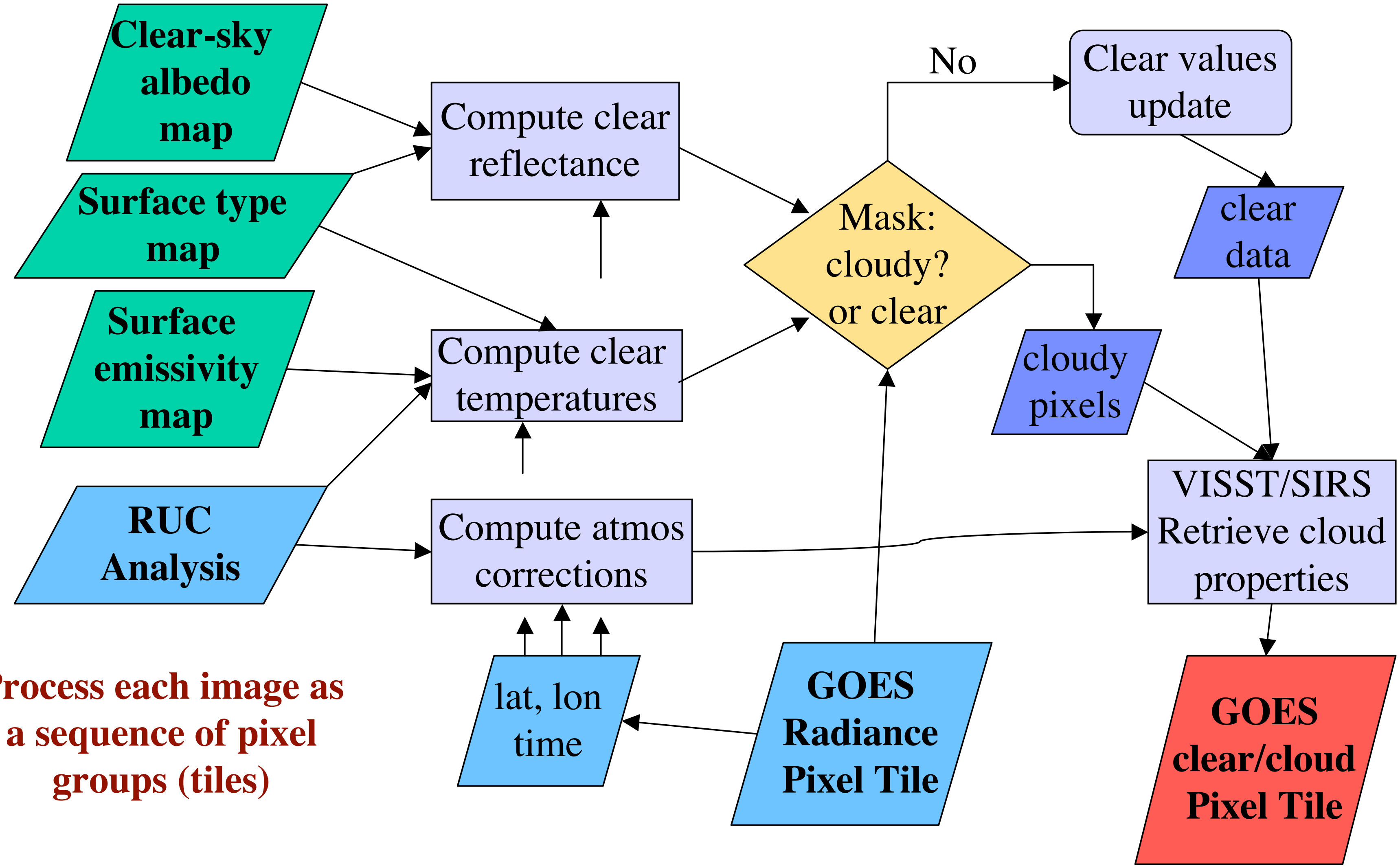
- **CERES clear-sky albedo, surface emissivity (10', 1°)**

  clear-sky reflectance, brightness temperature => cloud detection/retrieval

- **Theoretical cloud reflectance & emittance models**

  describes angular variation for range of re and □=> cloud detection/retrieval

METHODOLOGY FOR EACH IMAGE TIME



Process each image as a sequence of pixel groups (tiles)

CLOUD MASK

- To detect clouds, the radiances for cloud-free (clear) scene must be known

- Determine clear-sky albedos and surface emissivities after initial processing of data

  - start with CERES values and update

- Use RUC surface temperatures & profiles to estimate clear-sky brightness temperatures

- Must account for angular dependence: bidirectional reflectance models to estimate clear-sky reflectance for each pixel

- Estimate thresholds based on uncertainties in models & spatial/temporal variability of the clear radiances

CLEAR-SKY RADIANCE CHARACTERIZATION

- **Predict radiance a given satellite sensor would measure for each channel if no clouds are present**

- **Estimate uncertainty based on spatial & temporal variability & angular model errors**

- **Develop set of spectral thresholds for each channel**

  - Solar, uses reflectance, ρ

  - IR, use temperature, T

  brightness temperature difference, BTD = $T_{\lambda 1} - T_{\lambda 2}$

  typically, BTD(3.7-11) or BTD(11-12)

CLEAR-SKY REFLECTANCE, SOLAR

- **Estimate overhead-sun albedo, $\square_o = \square(\mu_o = 1)$**

  derived empirically with initial runs usingCERES VIRS data,
  then updated for each month using GOES

- **Estimate albedo at given local time, $\square(\mu_o) = \square_o \square_o(\mu_o)$**

  directional reflectance model $\square_o(\mu_o)$ derived for each IGBP type using VIRS

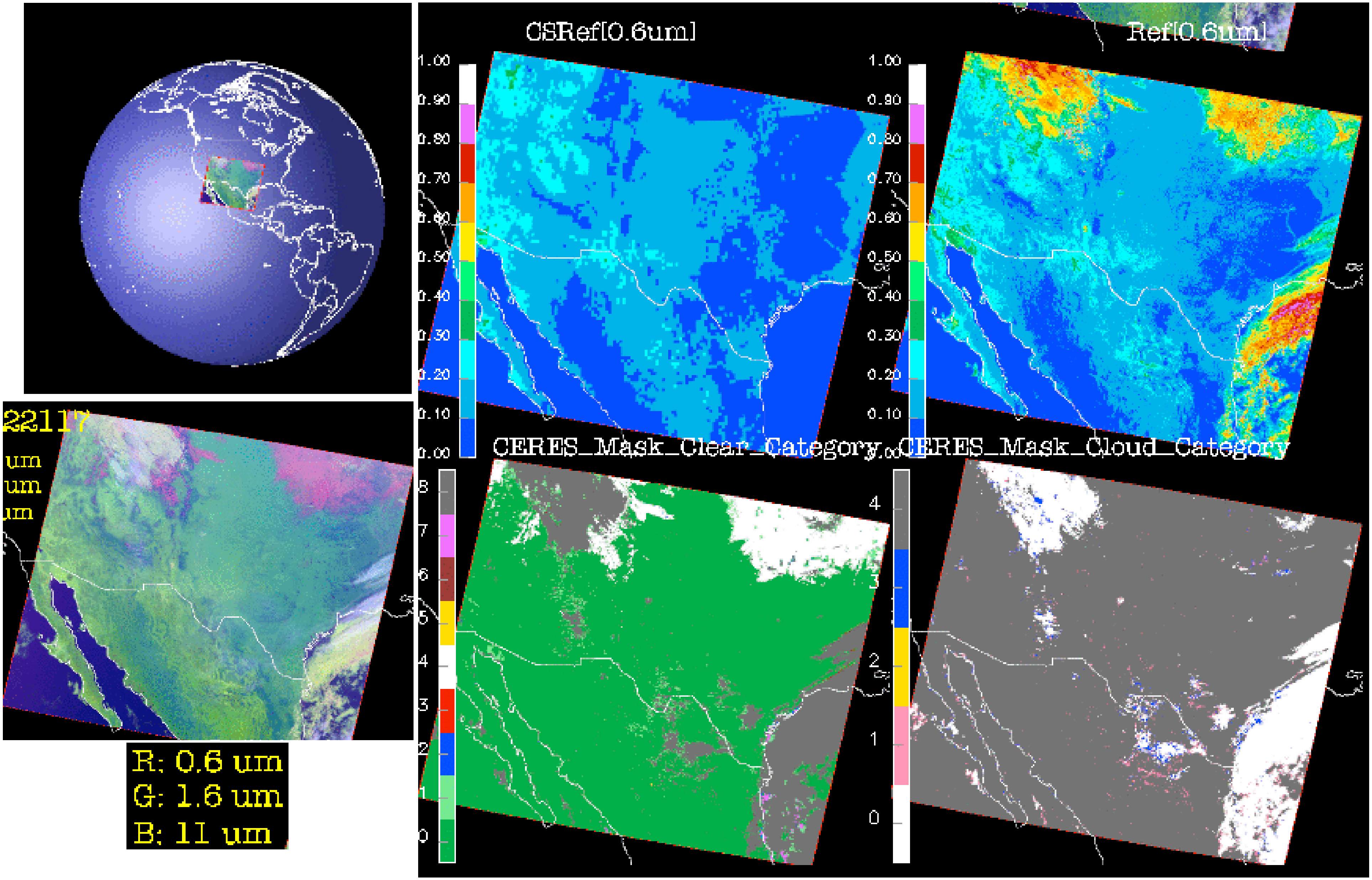
- **Estimate reflectance for given viewing angles, $\square(\mu_o, \mu, \square) = \square(\mu_o)\, \square(\mu_o, \mu, \square)$**

  bidirectional reflectance (BRDF) model $\square$ selected for each surface type

  from Kriebel (1978), Minnis & Harrison (1984), Suttles et al. (1988)

- **Add uncertainty to set reflectance threshold, $\square_T(\mu_o, \mu, \square) = \square + \square\square(\mu_o, \mu, \square)$**

PREDICTED CLEAR-SKY & OBSERVED VIS REFLECTANCE & CLOUD MASK
1700 UTC,12/21/00



CLEAR-SKY TEMPERATURE, INFRARED

- **Estimate surface emissivity, $\epsilon_s(x,y)$**

  derived empirically with using ISCCP AVHRR DX, VIRS, then Terra MODIS; water & snow theoretical models

- **Estimate radiance leaving the surface, $L_s = \epsilon_s B(T_{skin}) + (1-\epsilon_s)L_{ad}$**

  L_{ad} = downwelling atmo radiation, T_{skin} = skin temperature from model / obs

- **Estimate TOA brightness temperature, $B(T_{cs}) = (1-\epsilon_a)L_s + \epsilon_a L_{au}$**

  L_{au} = upwelling atmo radiation, ϵ_a = effective emissivity of atmo

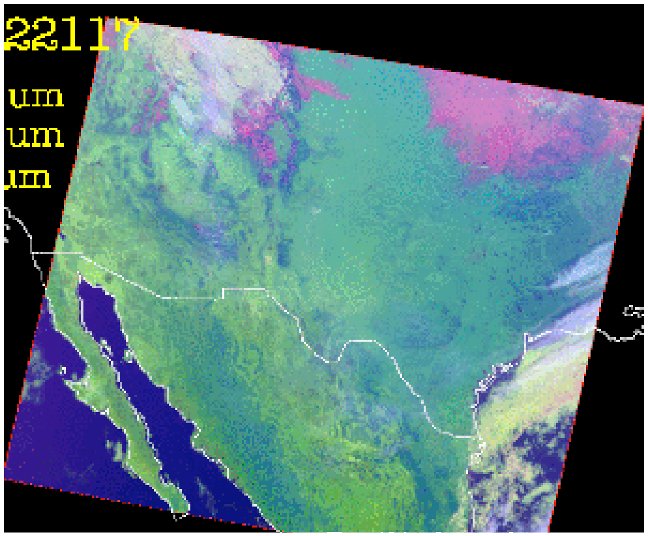
  layer absorption emission computed using T/RH profile, correlated k-dist

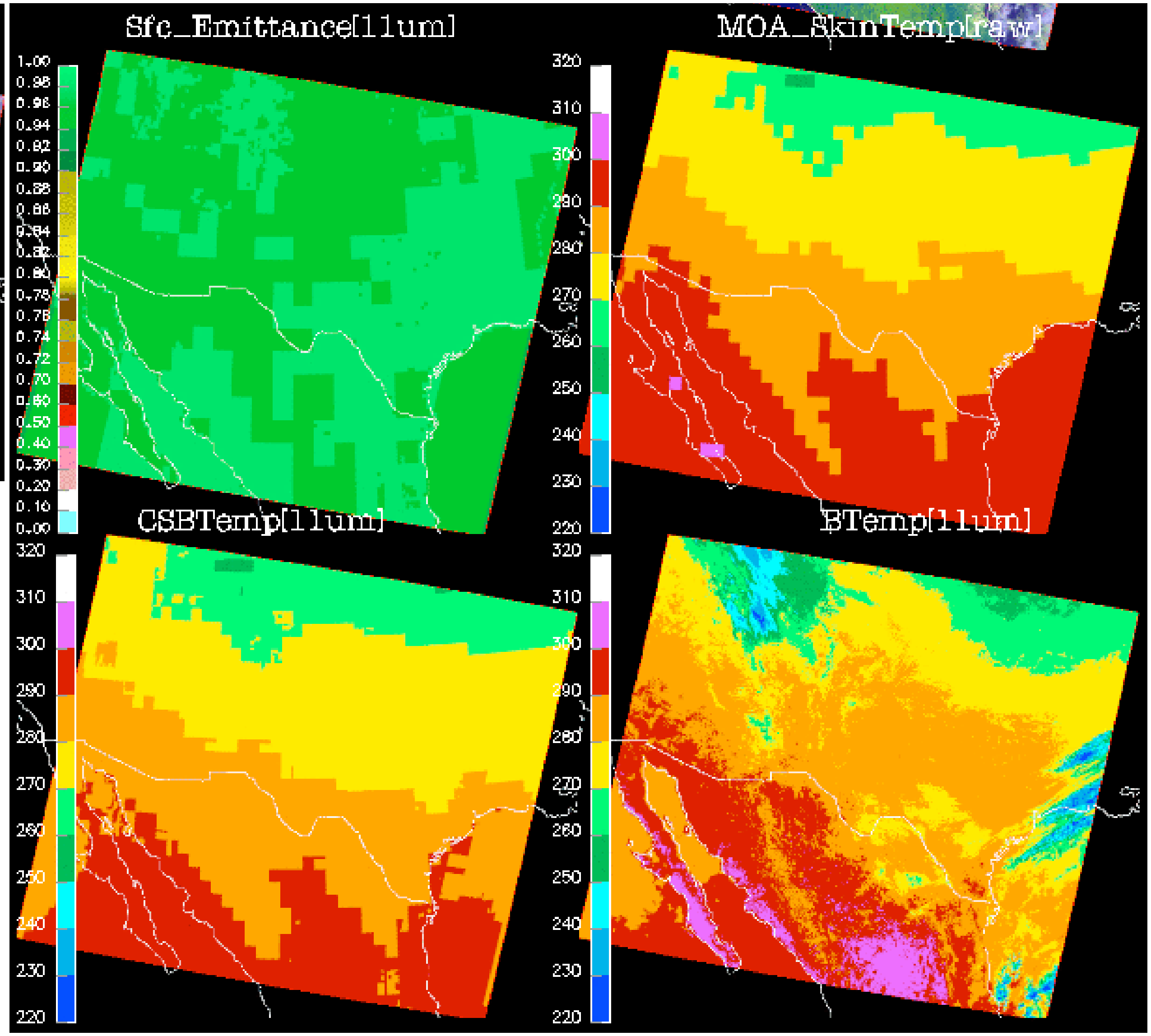
- **Add uncertainty to set T or BTD thresholds, $T_T(\mu) = T_{cs}(\mu) + \Delta T(\mu)$**

  - reflected solar component included in 3.7-4.0 µm estimate

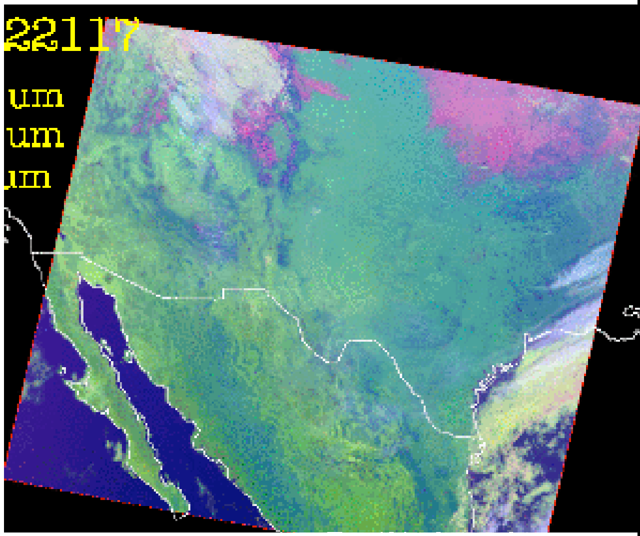
PREDICTED CLEAR-SKY & OBSERVED IR TEMPERATURE

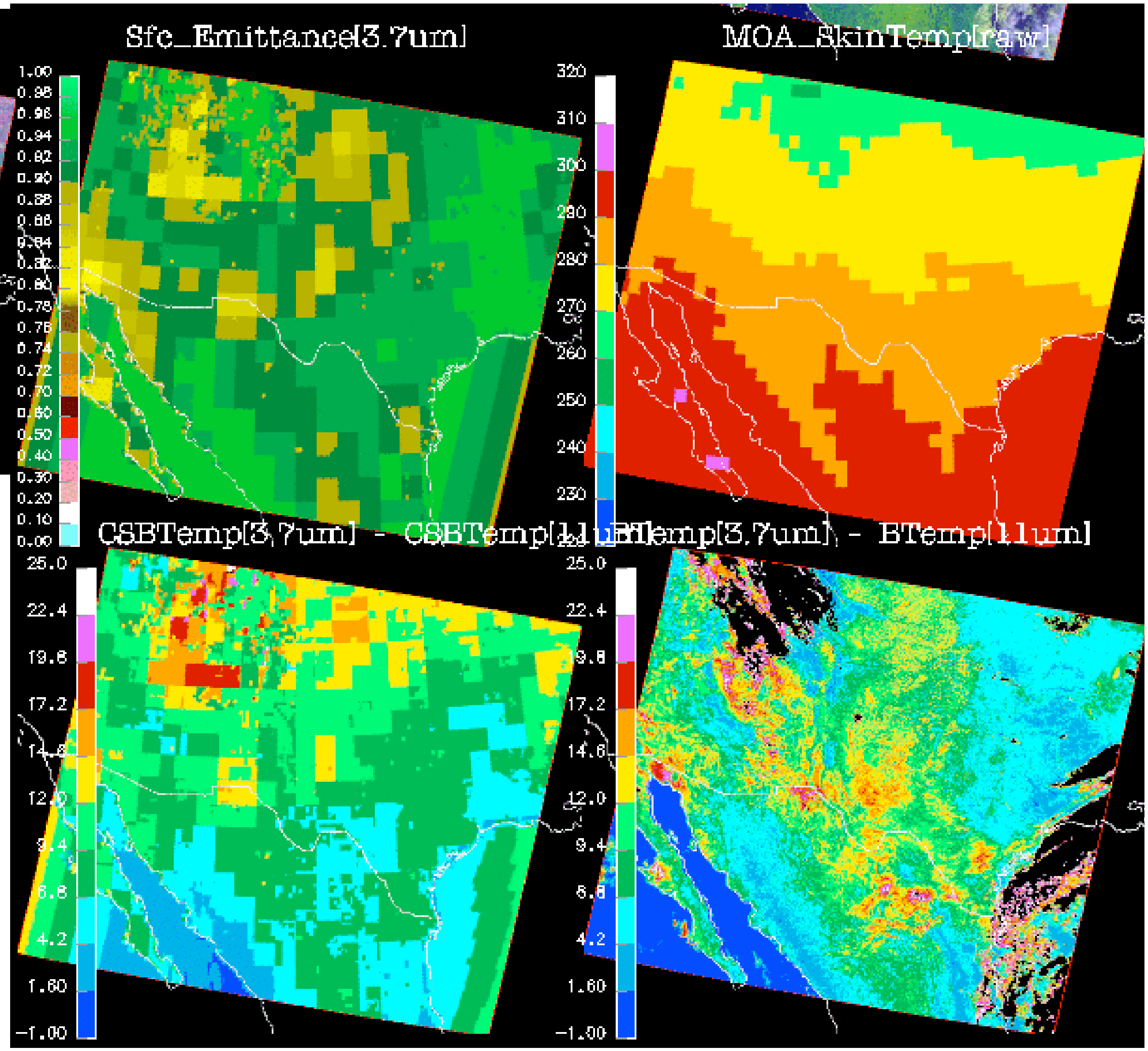
1700 UTC,12/21/00





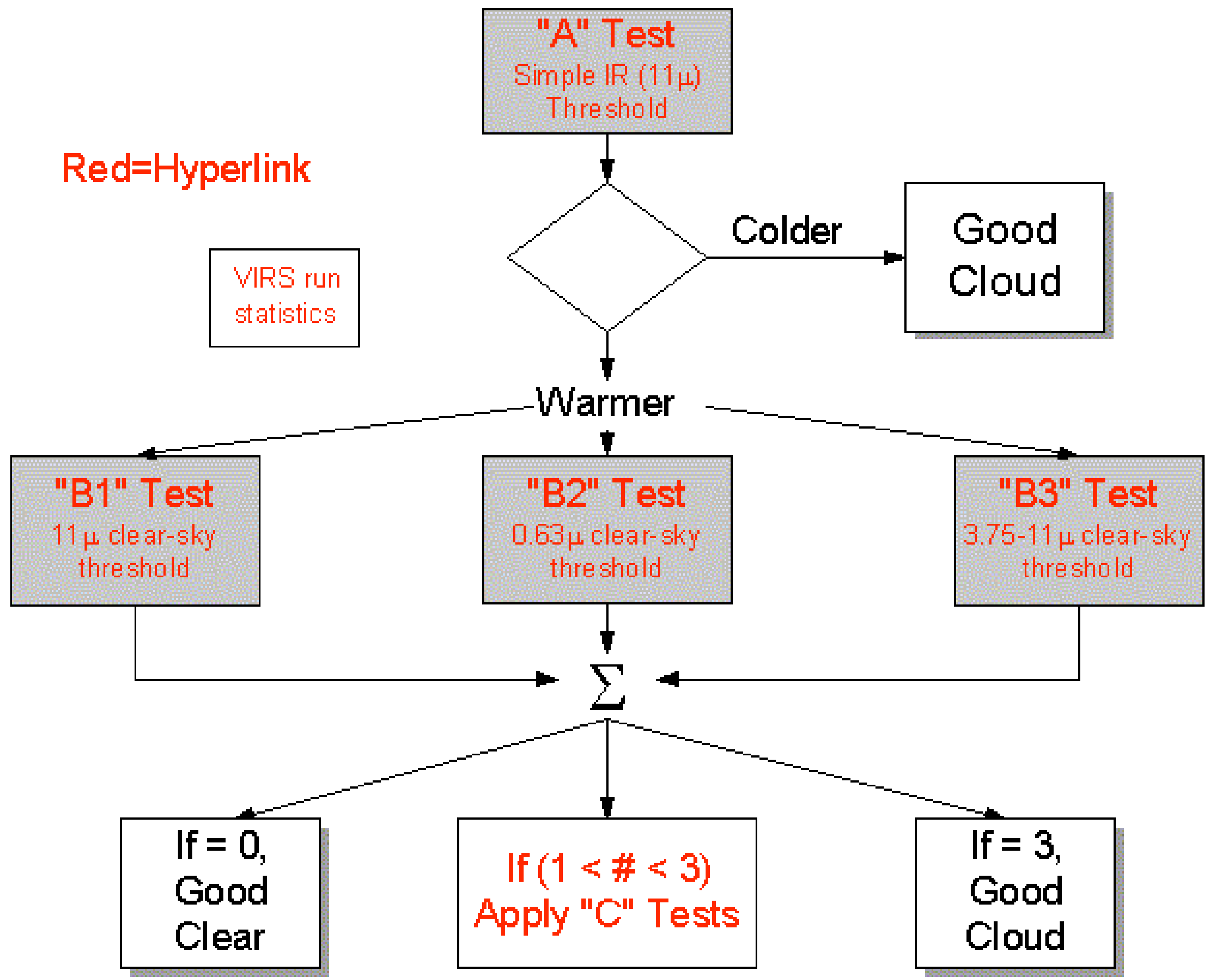
PREDICTED CLEAR-SKY & OBSERVED BTD (3.7 - 11)
1700 UTC,12/21/00



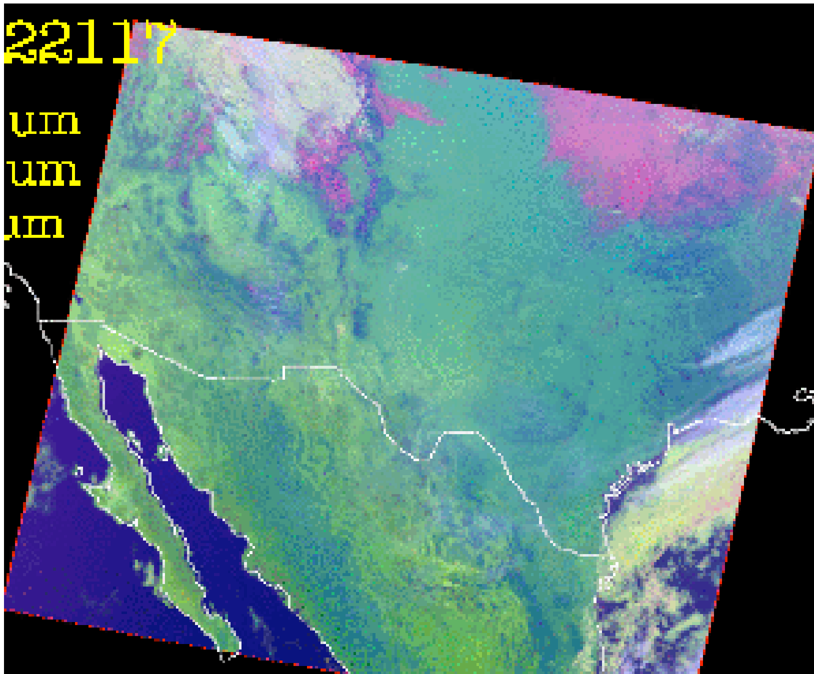


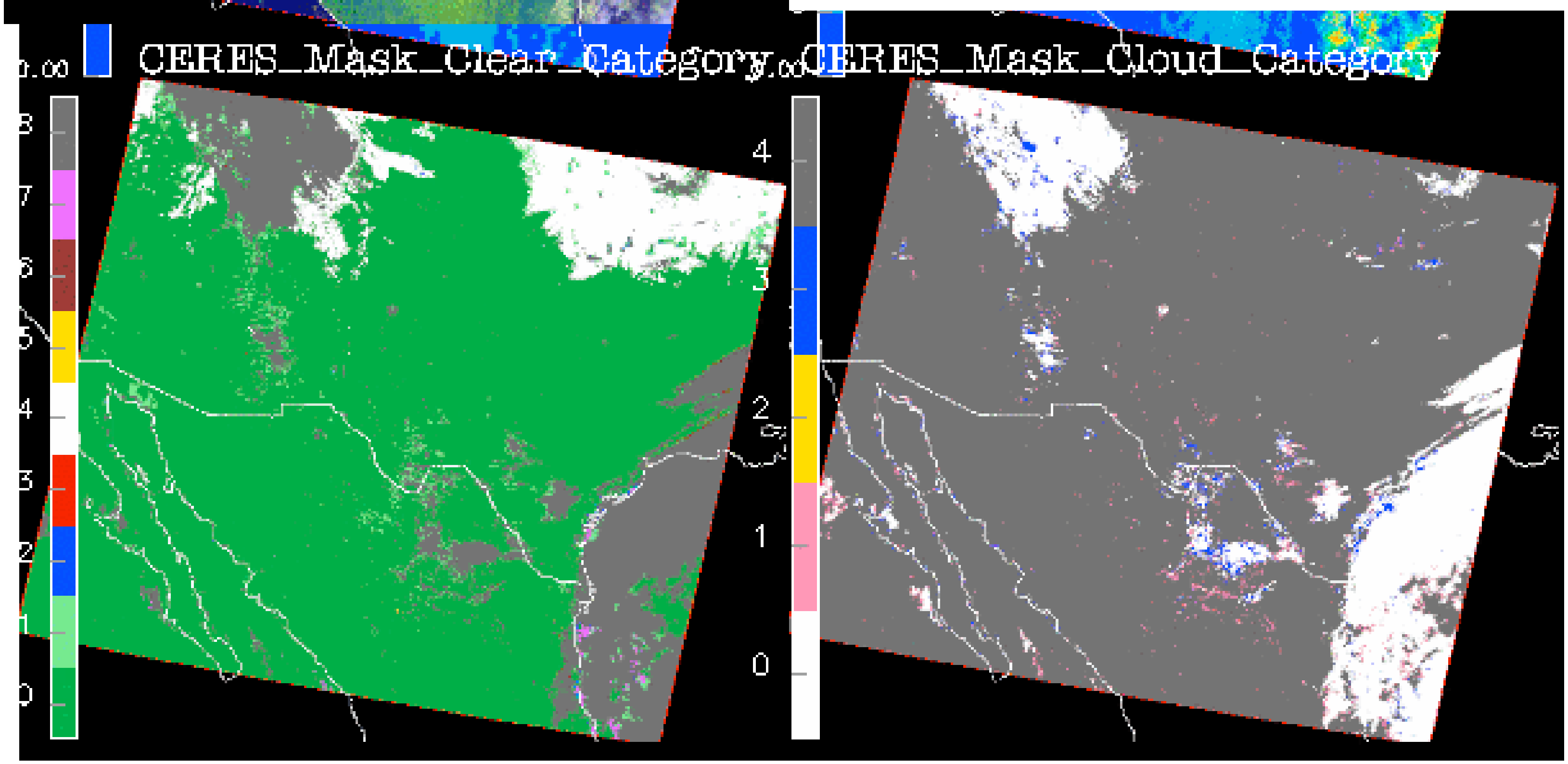
STANDARD DAYTIME MASK ALGORITHM

Top Level Daytime Flow Chart

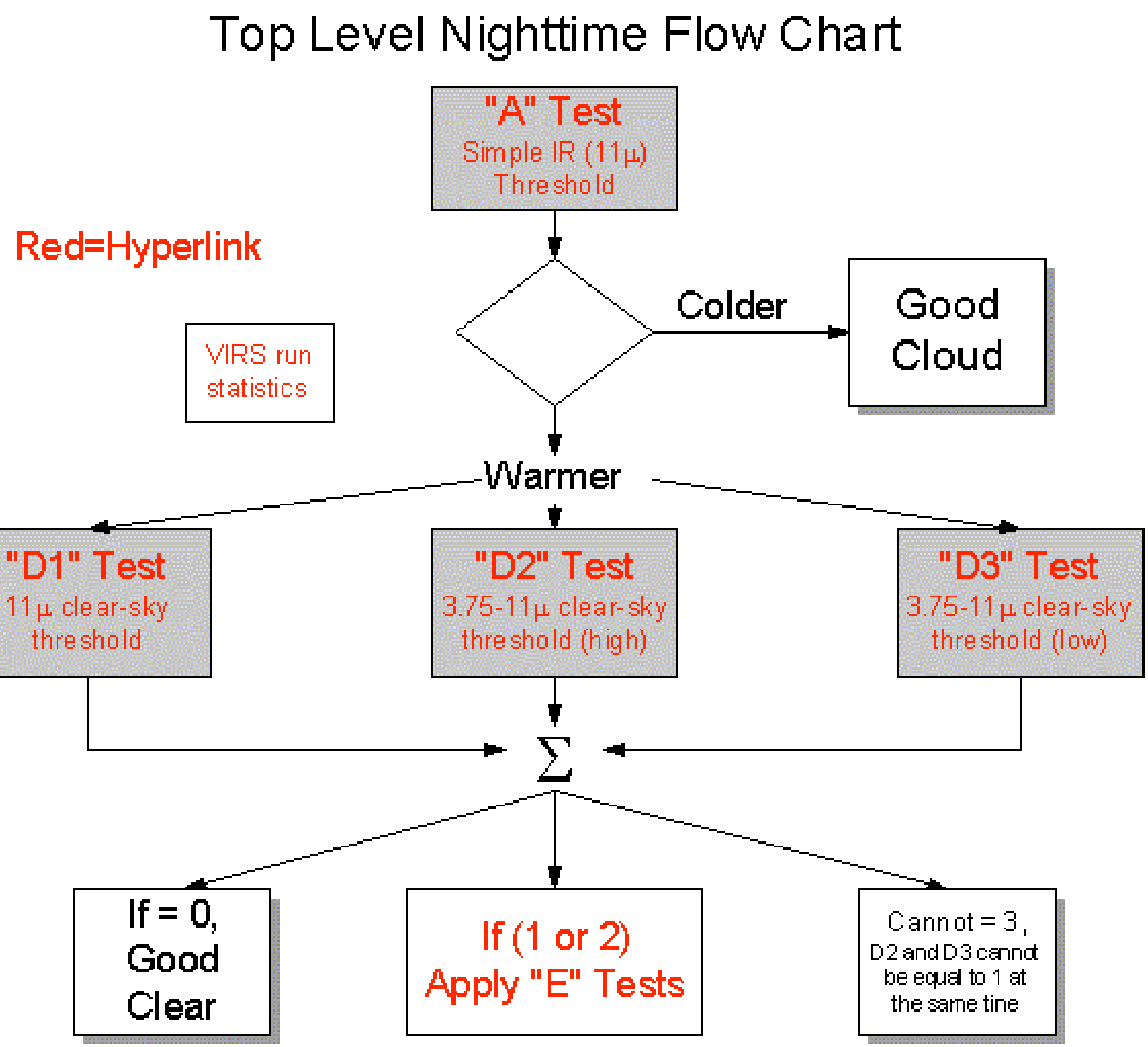


CERES CLOUD MASK 1700 UTC,12/21/00

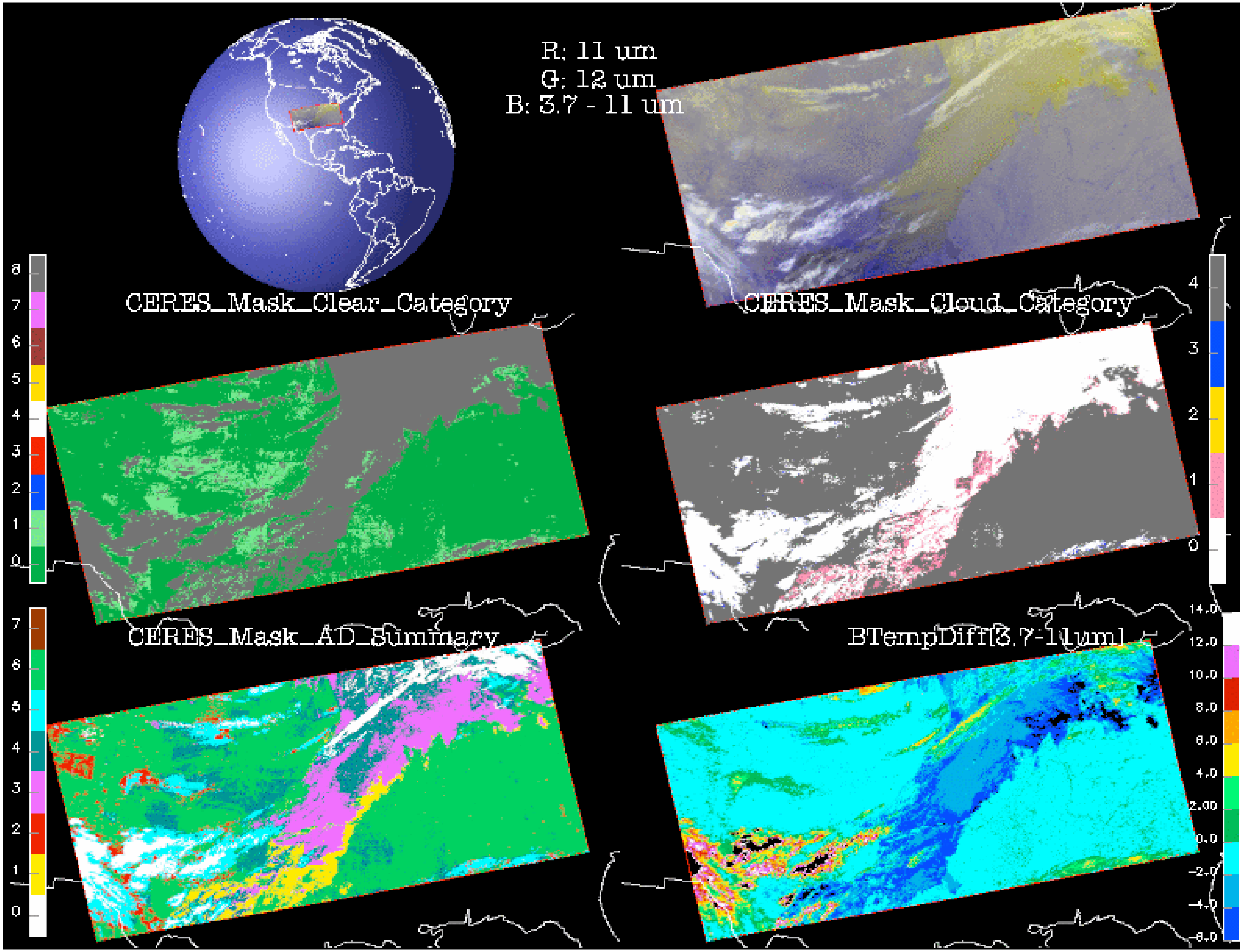




STANDARD NIGHTTIME MASK ALGORITHM



CERES CLOUD MASK & BTD(3.7 - 11) REFLECTANCE 0400 UTC,12/01/00



DAYTIME CLOUD RETRIEVALS

- VISST (Visible, infrared, solar-infrared, split-window technique)
  - physically based method using 0.65, 3.7, 11, & 12 μm
  - for cloudy pixels, match radiances to model values
- Yields more accurate cloud temperatures than simpler methods
  - adjusts temperature (altitude) of thin clouds
- Provides basis for determining phase
  - in most cases, ice & water models are distinct

Daytime Cloud Property Retrievals

- Derive cloud properties by matching observed radiances to model calculations for water droplets ($2 < r_e < 32$ μm) and ice crystals ($6 < D_e < 135$ μm) through reflectance and emittance parameterizations

- 3.9 μm (GOES Channel 2) used for particle size retrieval

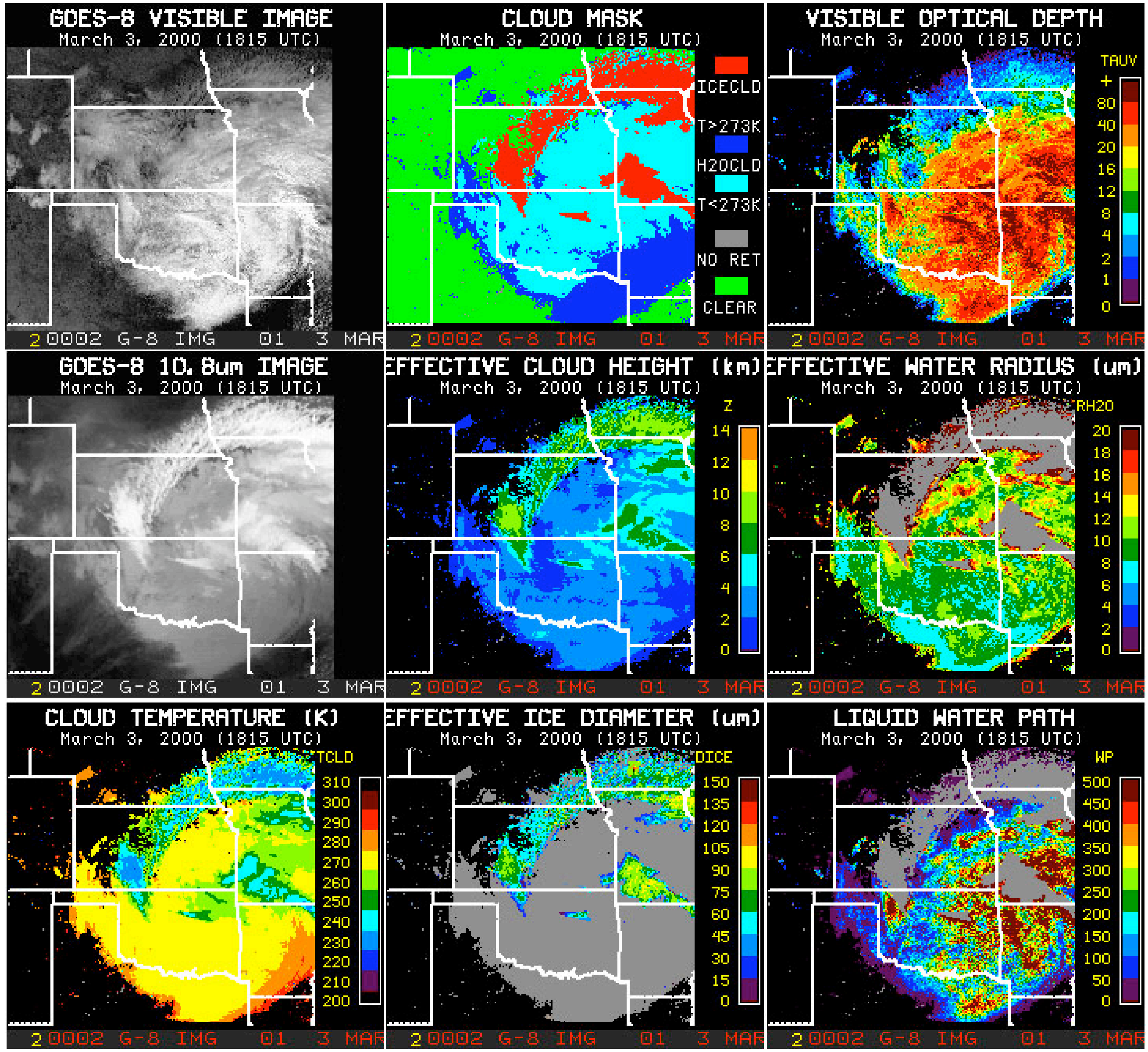
- Particle phase determined by:
  - (1) Best available model solution
  - (2) $T_{10.8}$ - $T_{12.0}$ Difference
  - (3) Visible/IR Layer Retrieval
  - (4) Retrieved Cloud Temperature

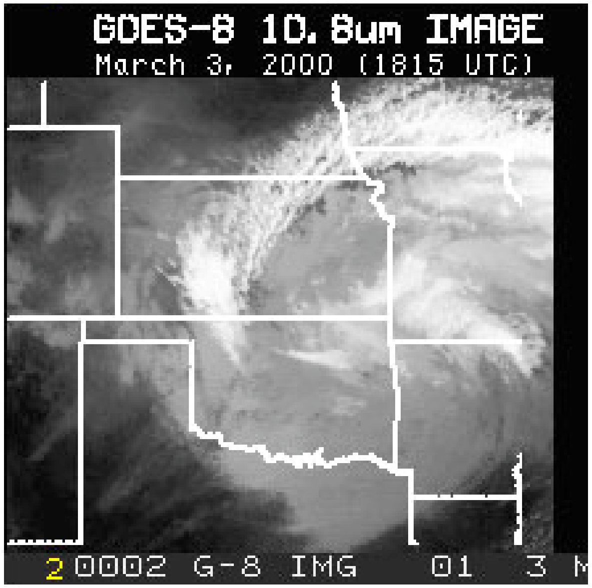
→ Cloud Tau, phase, r_e (D_e), LWP (IWP), Z_{cld} , T_{cld}

Cloud properties from GOES-8

1815 UTC

March 3, 2000

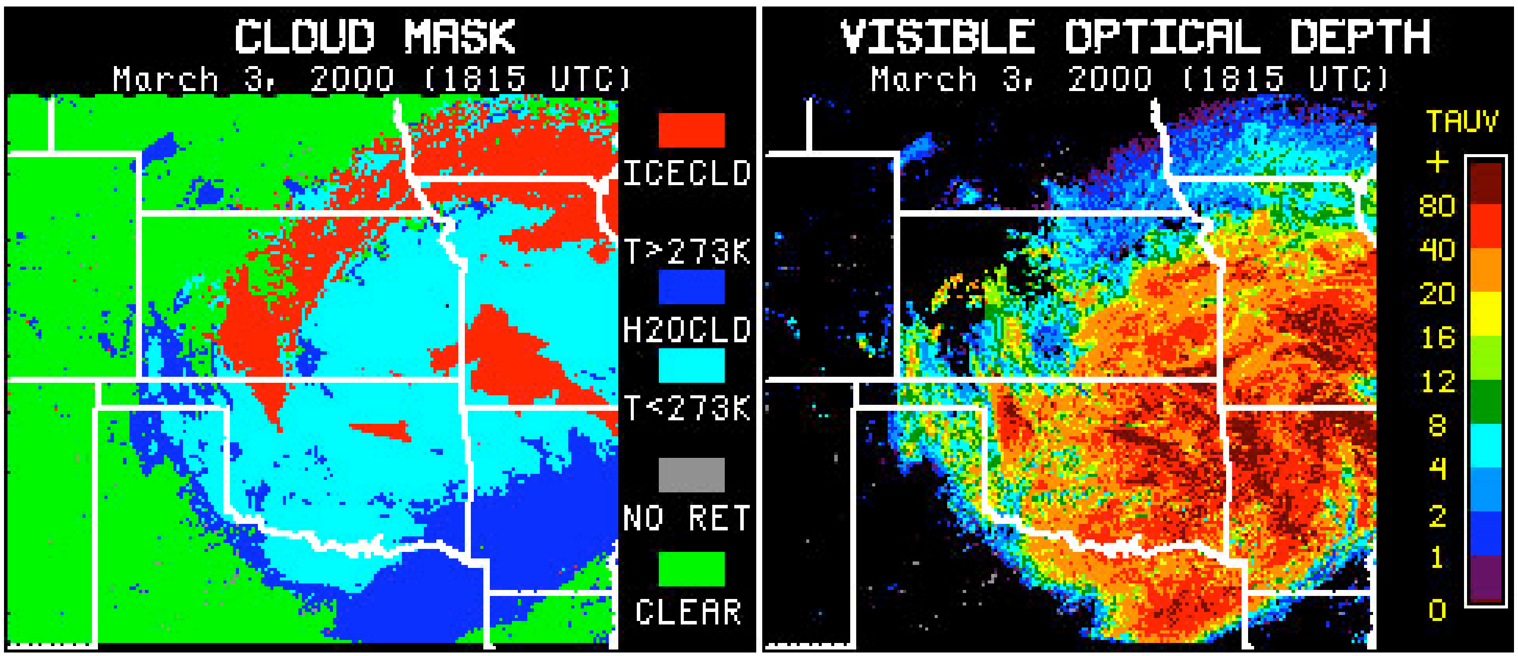


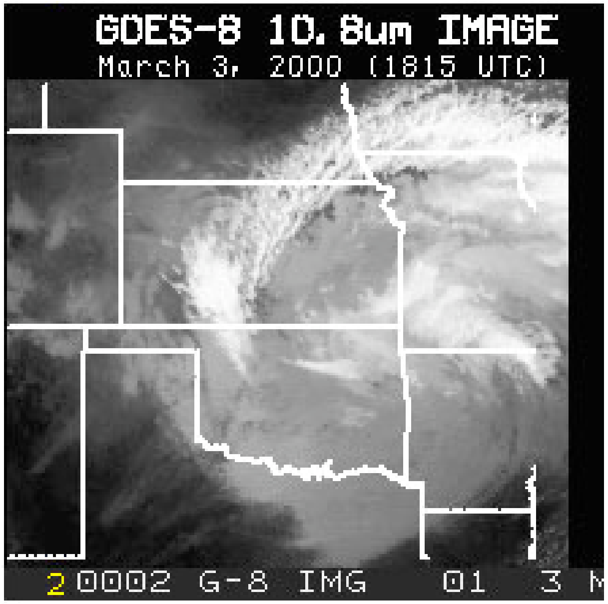


Cloud mask & optical depths from GOES-8

1815 UTC

March 3, 2000

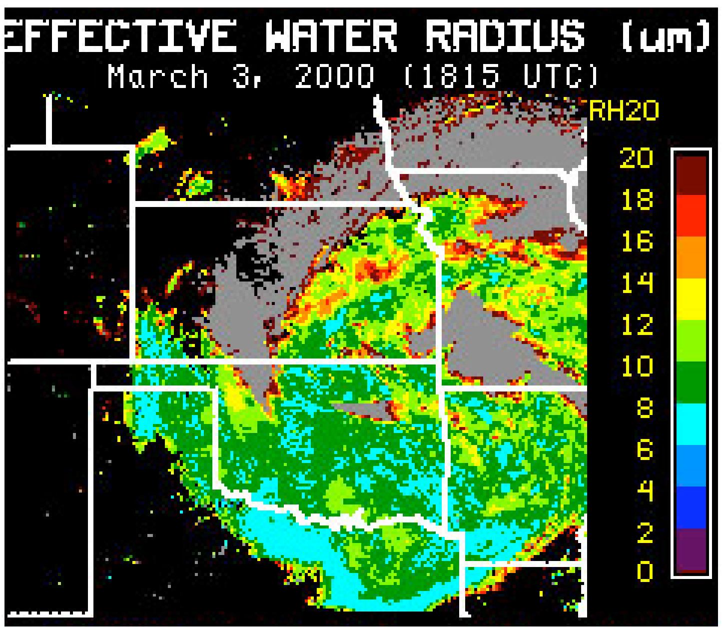


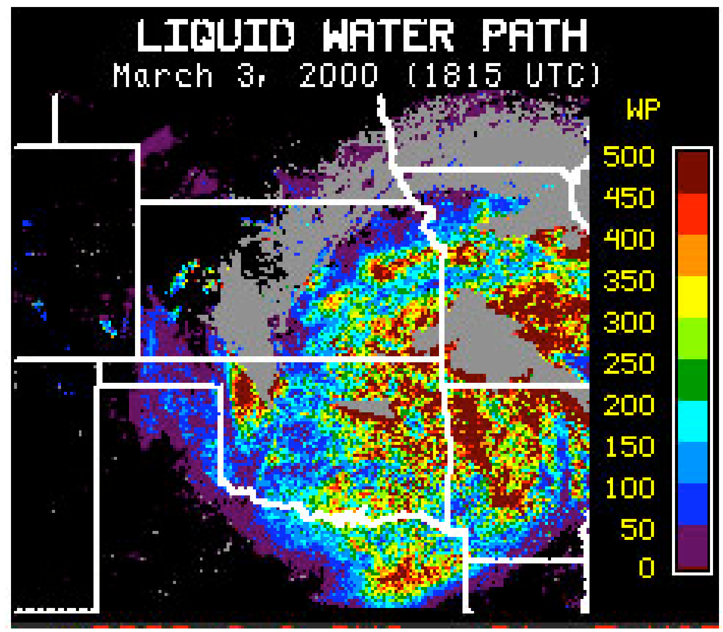


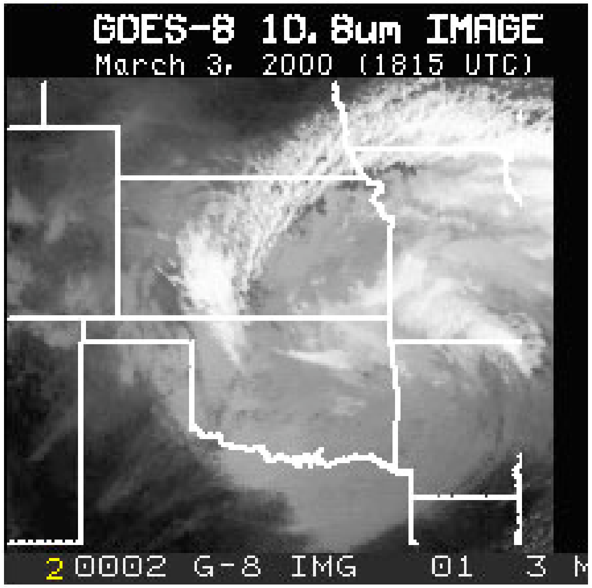
Cloud droplet radius &
LWP from GOES-8

1815 UTC

March 3, 2000



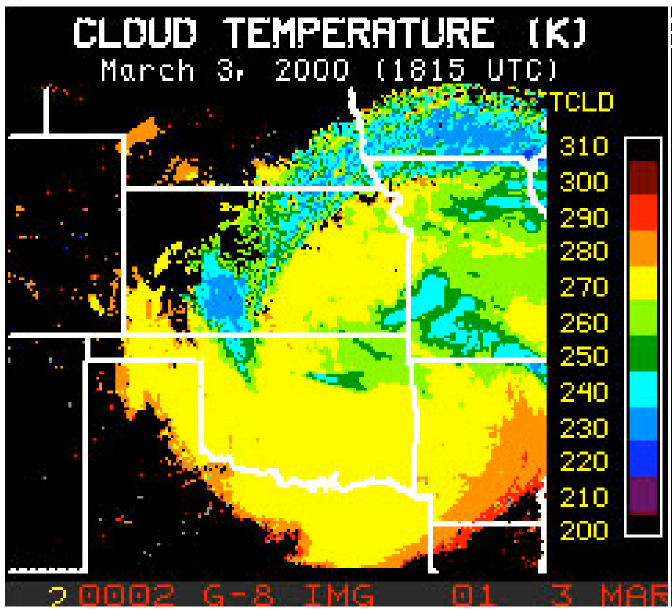


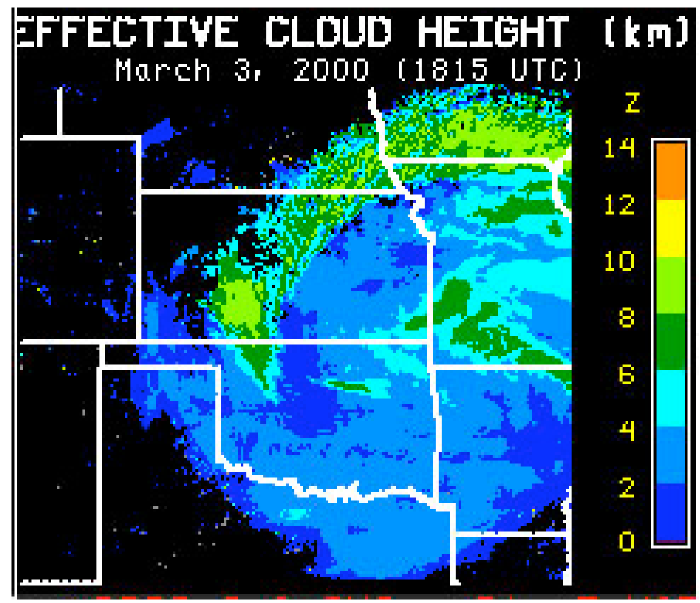


Cloud-top temperature
& height from GOES-8

1815 UTC

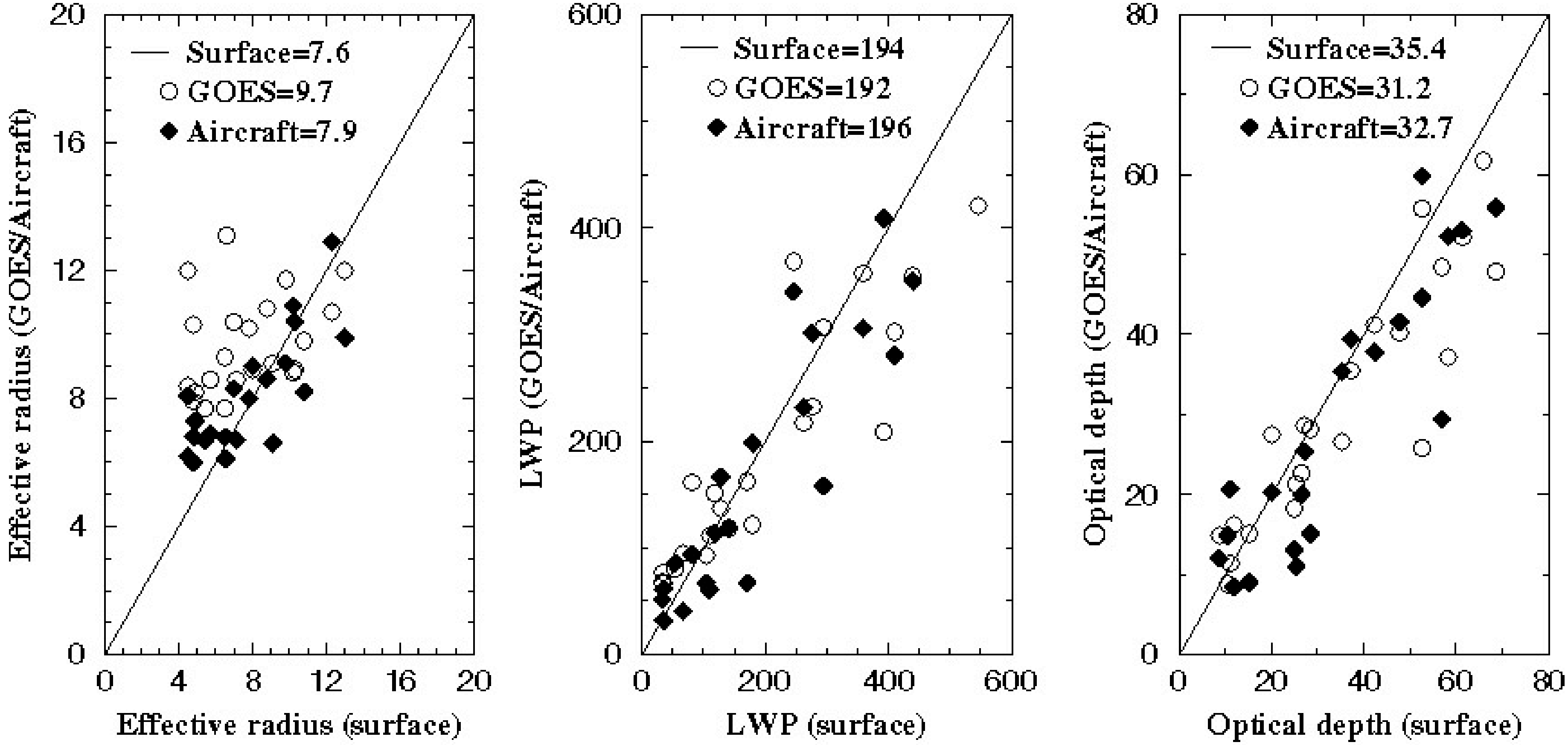
March 3, 2000





ARM-Sponsored Comparisons (March 2000)

Comparison of Surface, GOES and Aircraft Results (~10 hours)

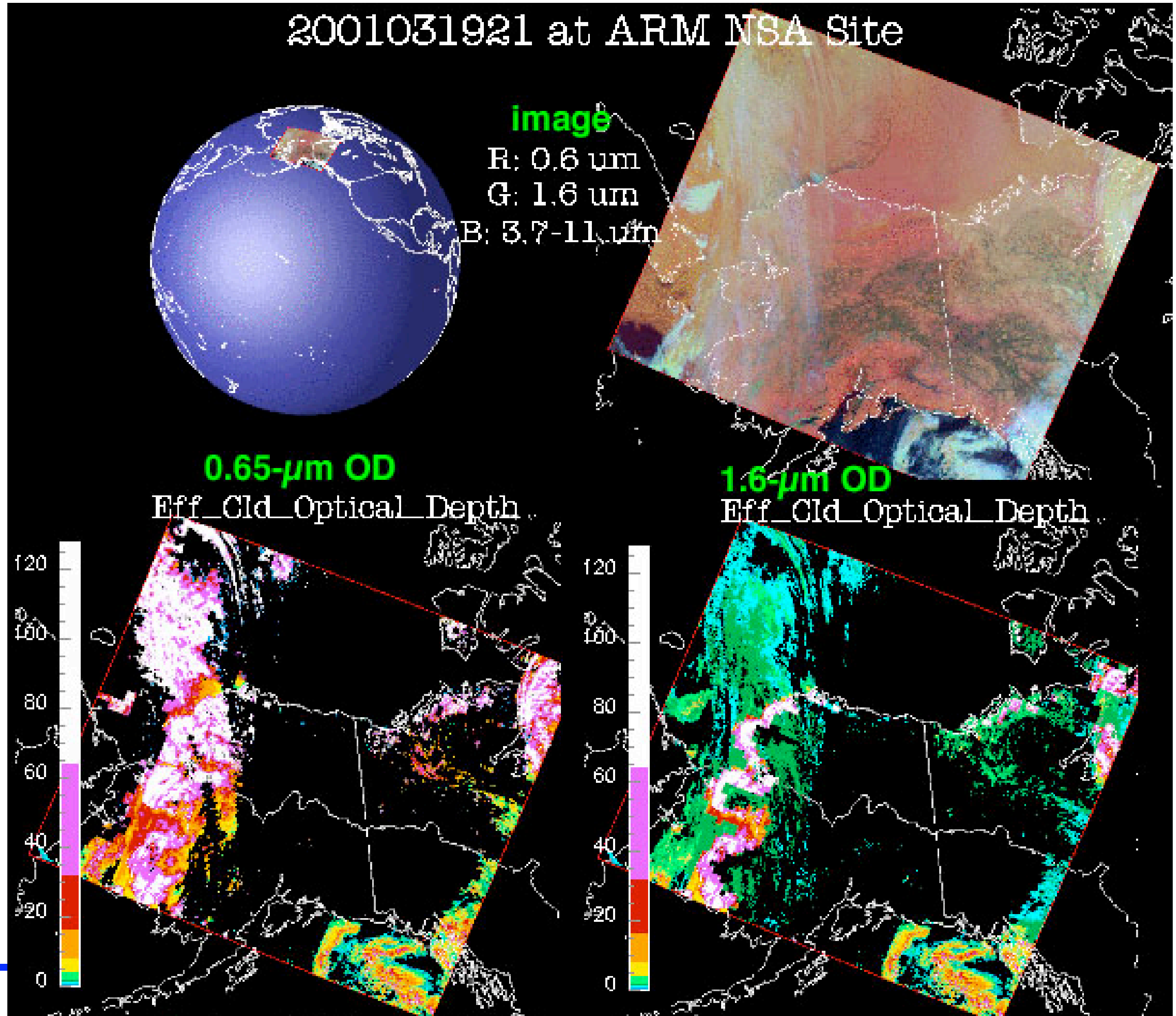


Comparison of Optical Depths (OD) from VISST & SINT, *Terra* MODIS

Northern Alaska

March 3, 2001

2100 UTC



Visible channel overestimates OD over snow & ice

1.6-μm yields more realistic value for OD

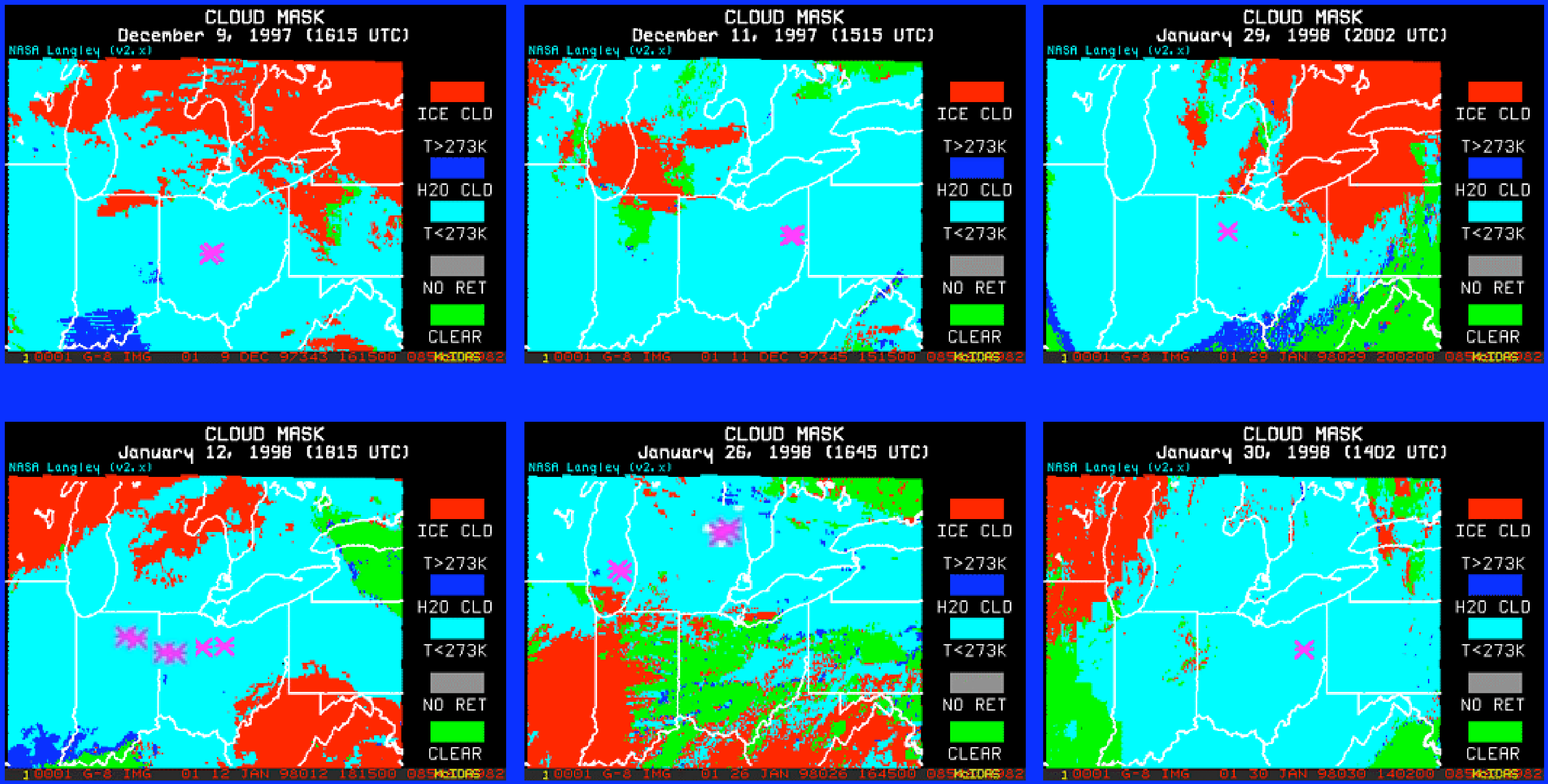
Comparison of Super-Cooled Liquid Water Cloud Properties Derived from Satellite and Aircraft Measurements

Validation of Satellite-Derived SLW Cloud Properties

How do satellite retrievals of Tcld, Re, LWP correspond to aircraft icing?

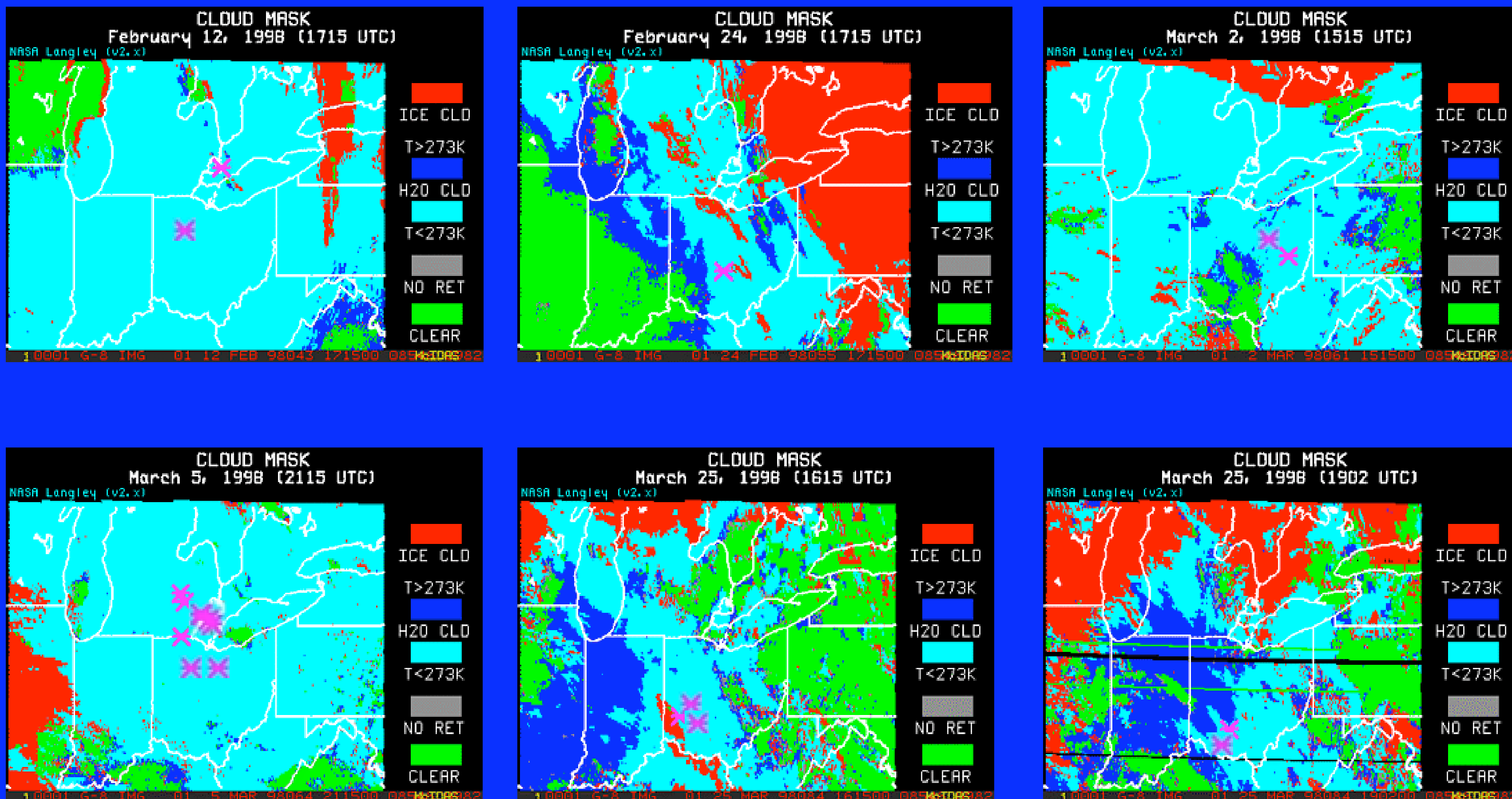
- Correlate with measurements from icing research aircraft (NASA GRC)
  - Winter 1998 NASA/FAA/NCAR Supercooled Large Droplet Research Project and compare satellite retrievals with:
- Correlate with PIREPS
  - 1998 Flight days
  - Jan 15 – Mar 30, 2003 (real-time runs to support Twin Otter flights)

GOES detects SLW for all 46 Twin Otter SLW cloud top penetrations (McDonough and Bernstein, 2000)



x - denotes Twin Otter cloud top penetrations

GOES detects SLW for all 46 Twin Otter SLW cloud top penetrations (McDonough and Bernstein, 2000)

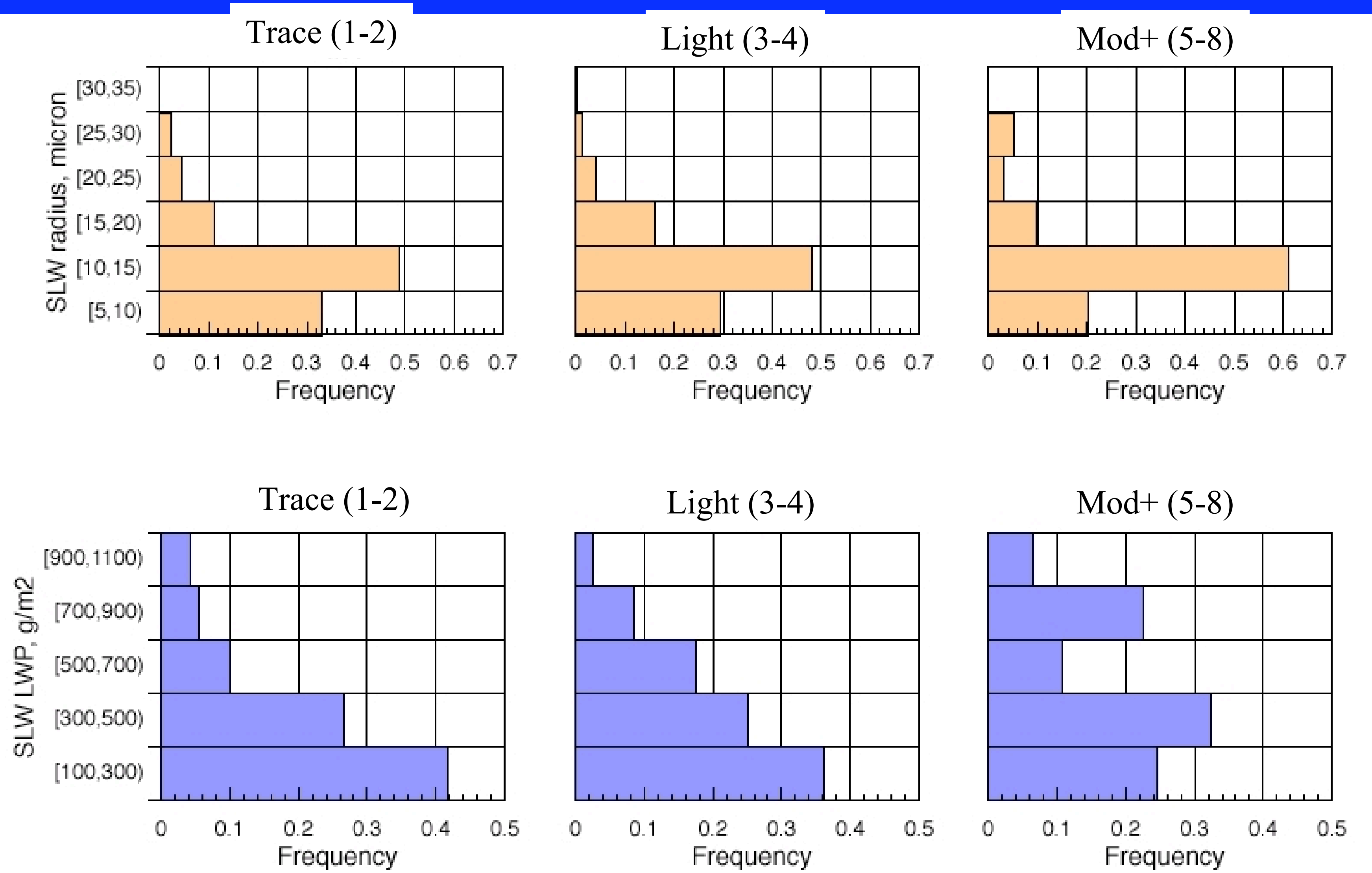


x - denotes Twin Otter cloud top penetrations

GOES SLW vs. PIREPS Icing

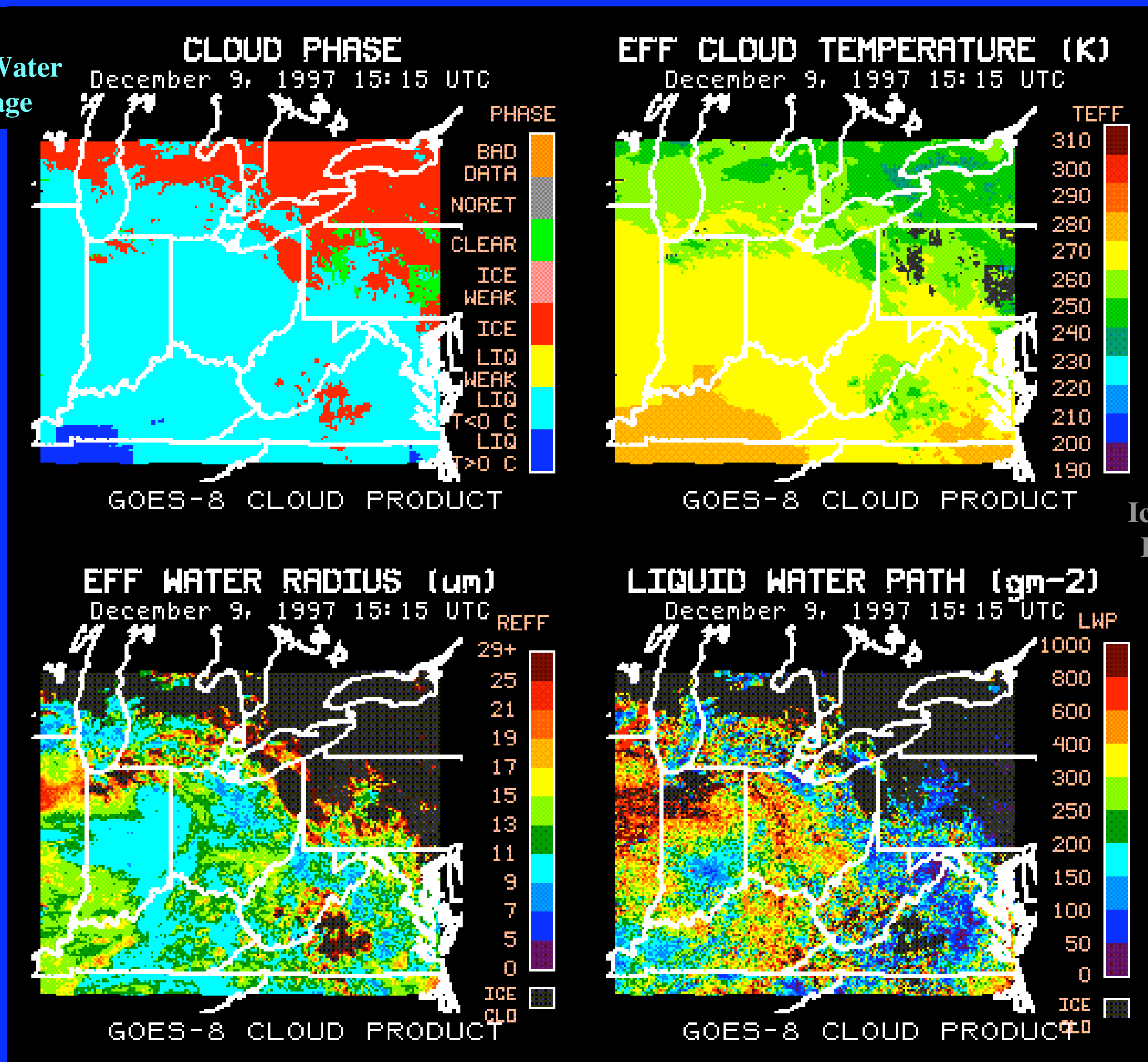
Compared to Positive icing PIREPS and provided there were no overcast ice clouds, LaRC GOES technique detected SLW 98% of the time (Smith et al., 2000)

Comparison of GOES Cloud Properties with PIREPS Icing Intensity
N=7800 (Jan-March, 2003)



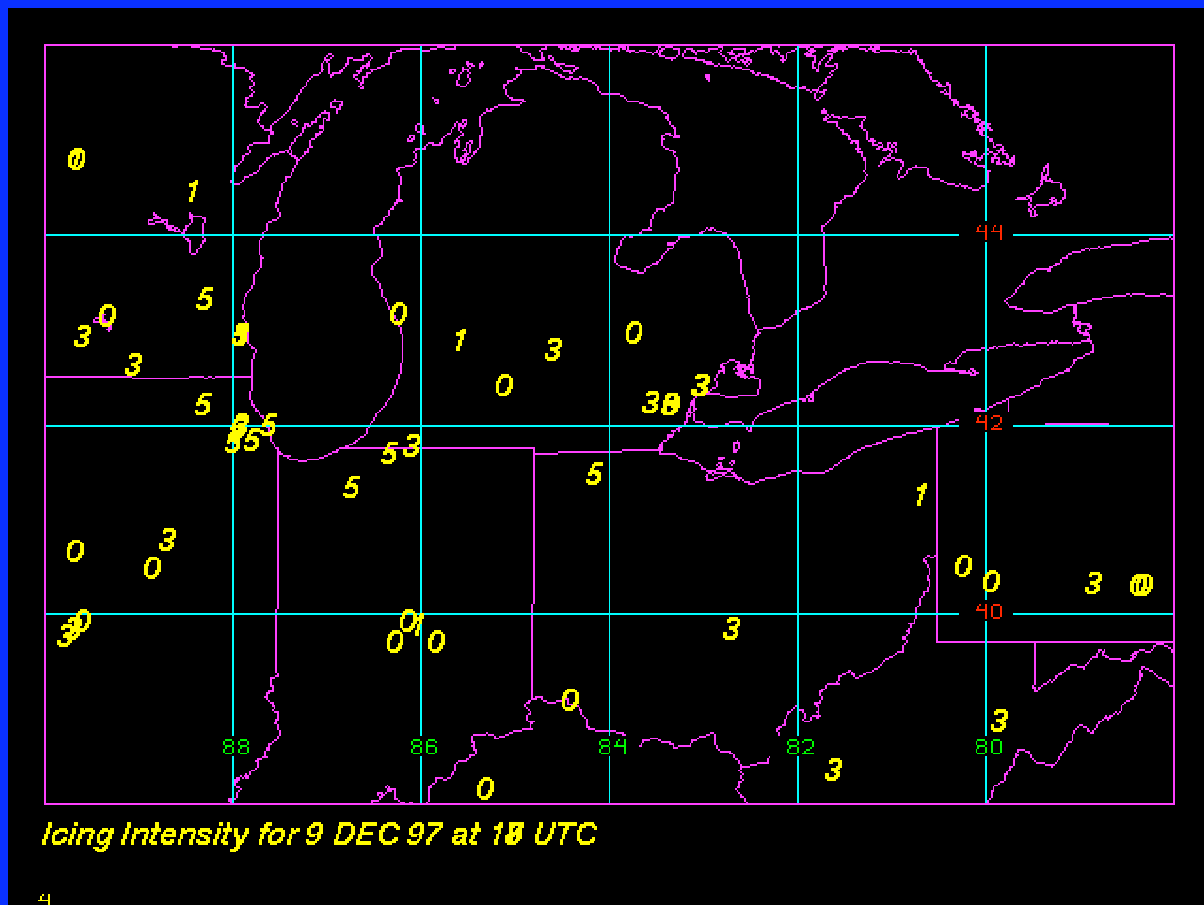
GOES-Derived Cloud Properties (Dec. 9, 1997)

Cyan indicates
Supercooled Liquid Water
In Cloud Mask Image

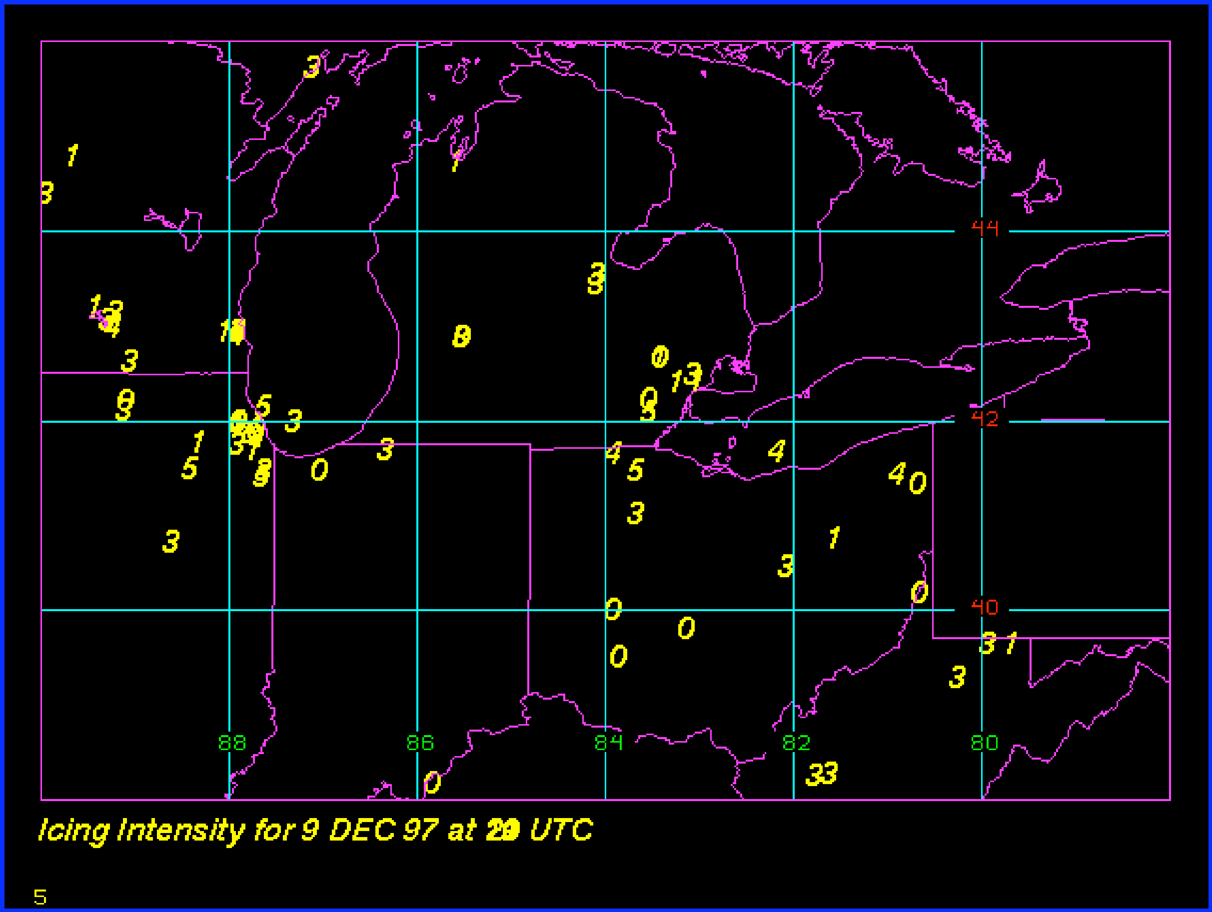


Ice Cloud Properties
In Grey not shown

PIREP Icing Intensity at 16-18 UTC Dec. 9, 1997

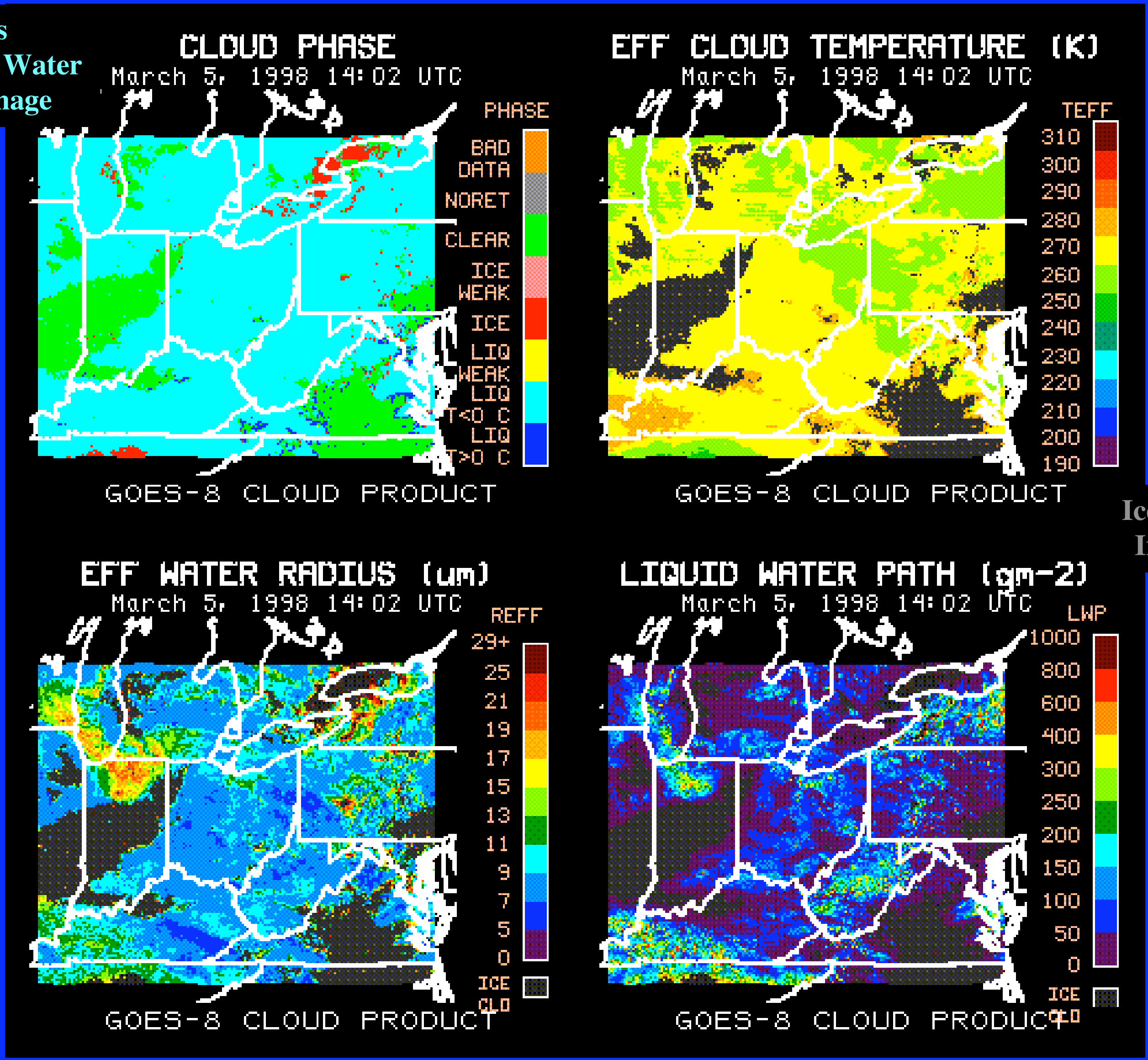


PIREP Icing Intensity
at 19-21 UTC Dec. 9, 1997



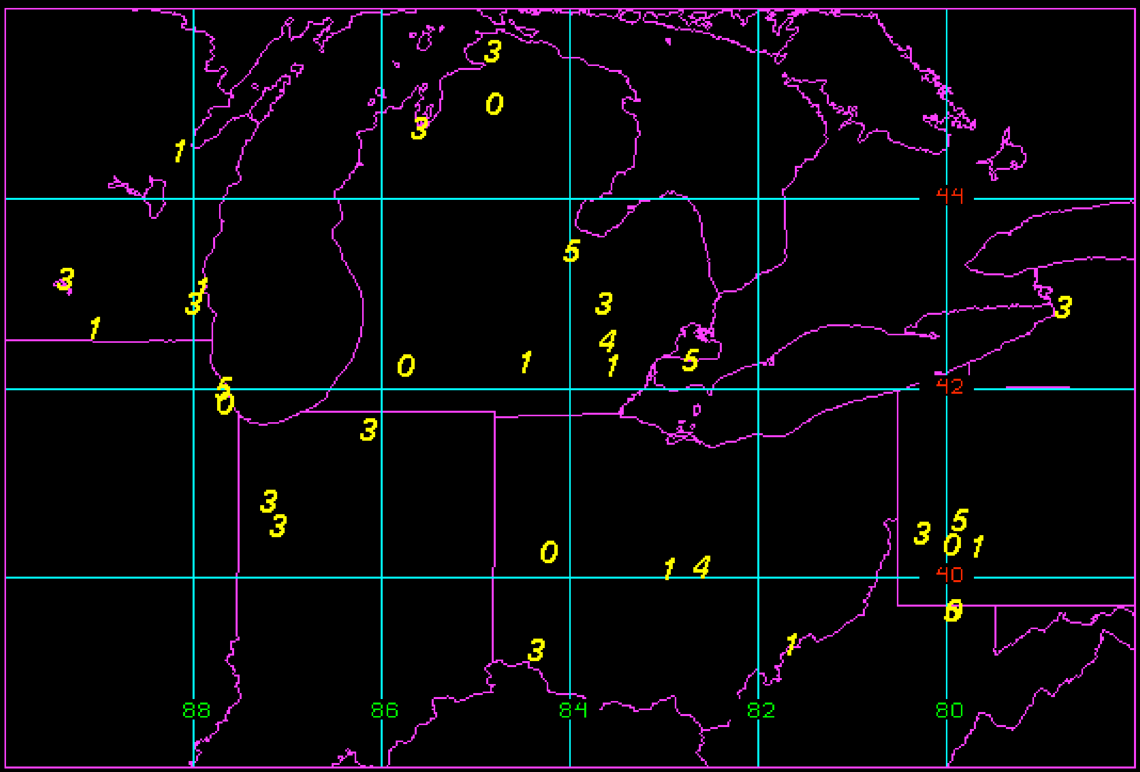
GOES-Derived Cloud Properties (March 5, 1998)

Cyan indicates
Supercooled Liquid Water
In Cloud Mask Image



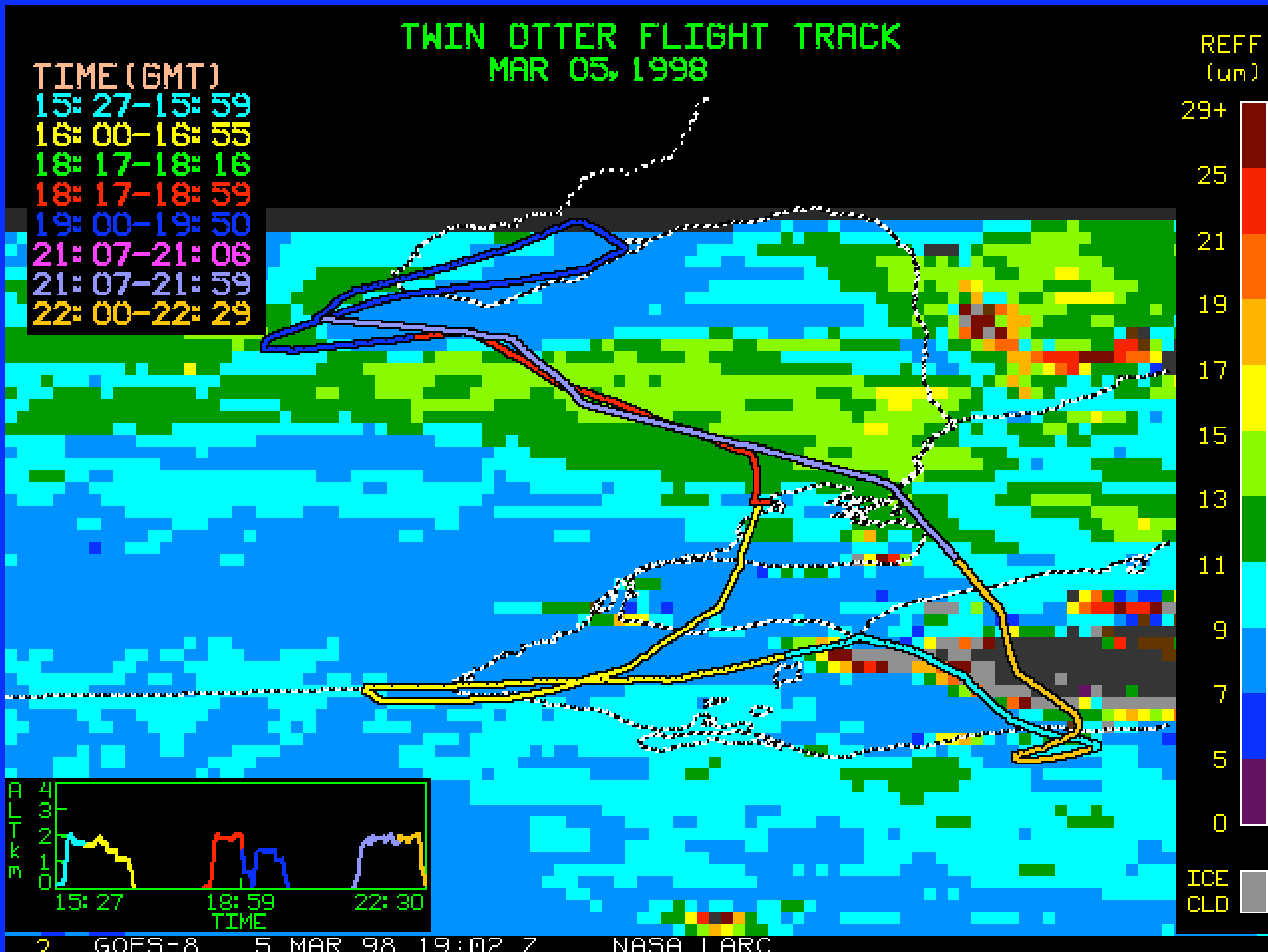
Ice Cloud Properties
In Grey not shown

PIREP Icing Intensity at 17-19 UTC Mar. 5, 1998

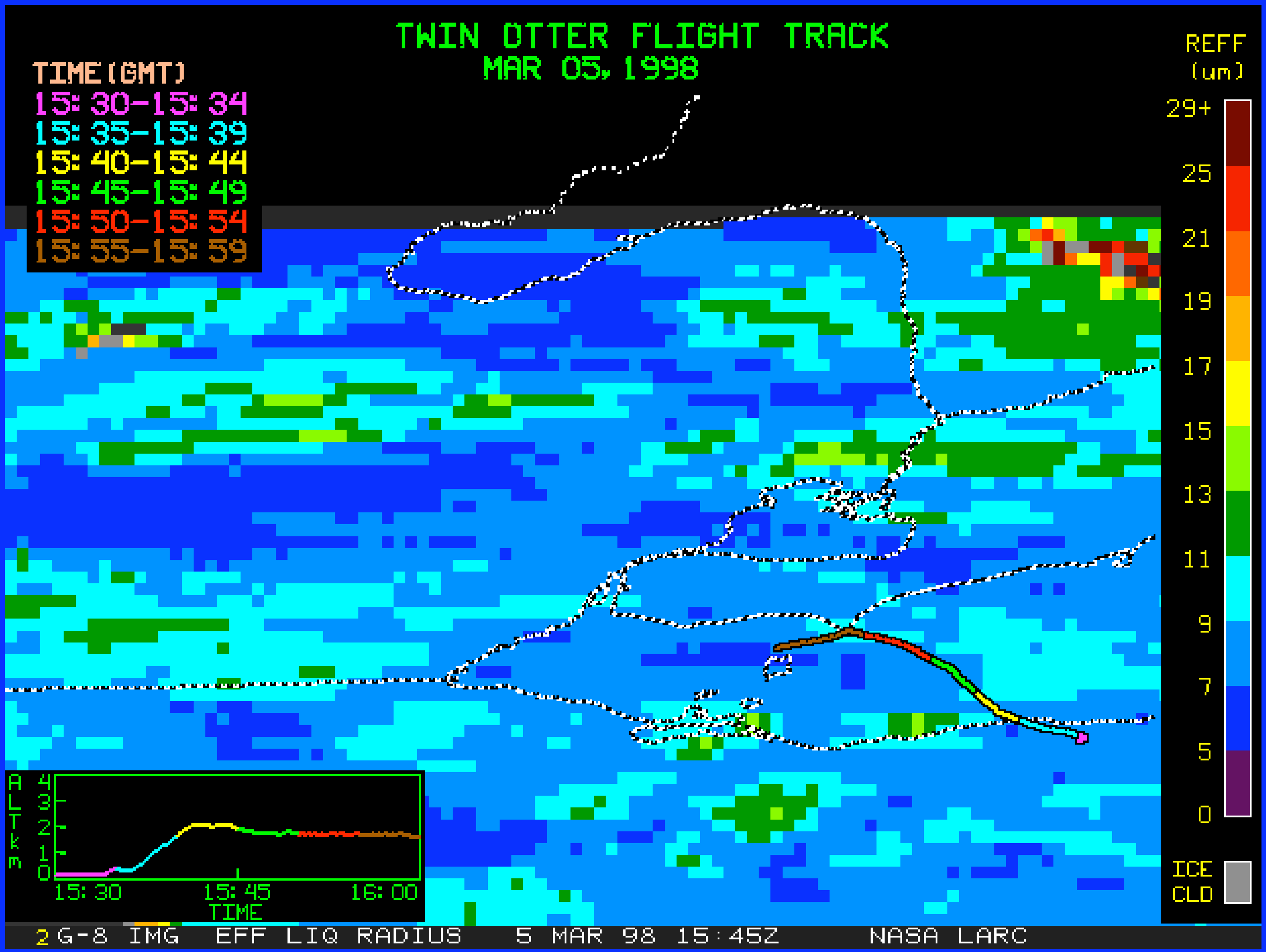


Icing Intensity for 5 MAR 98 at 18 UTC

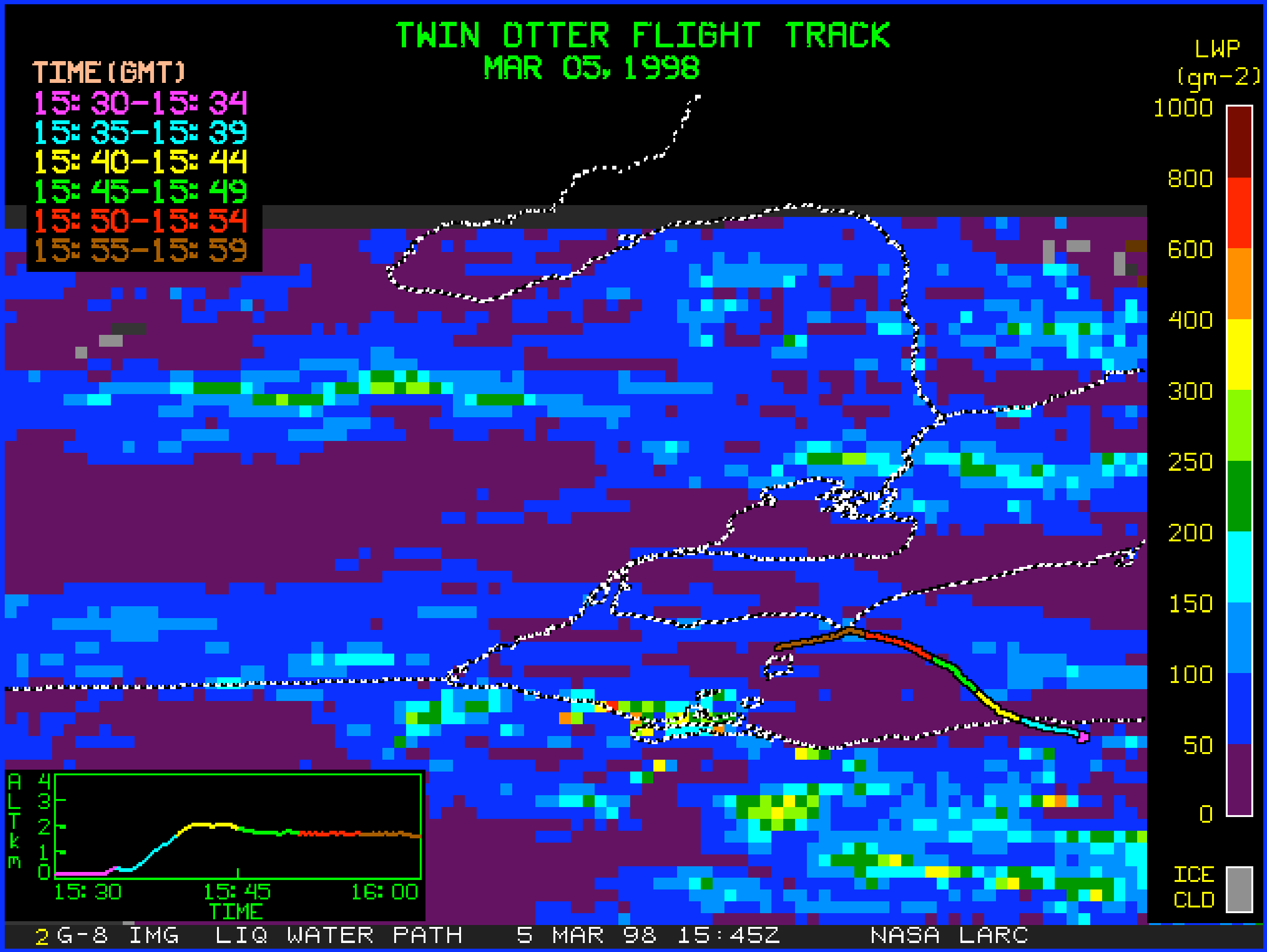
GOES Water Droplet Radius



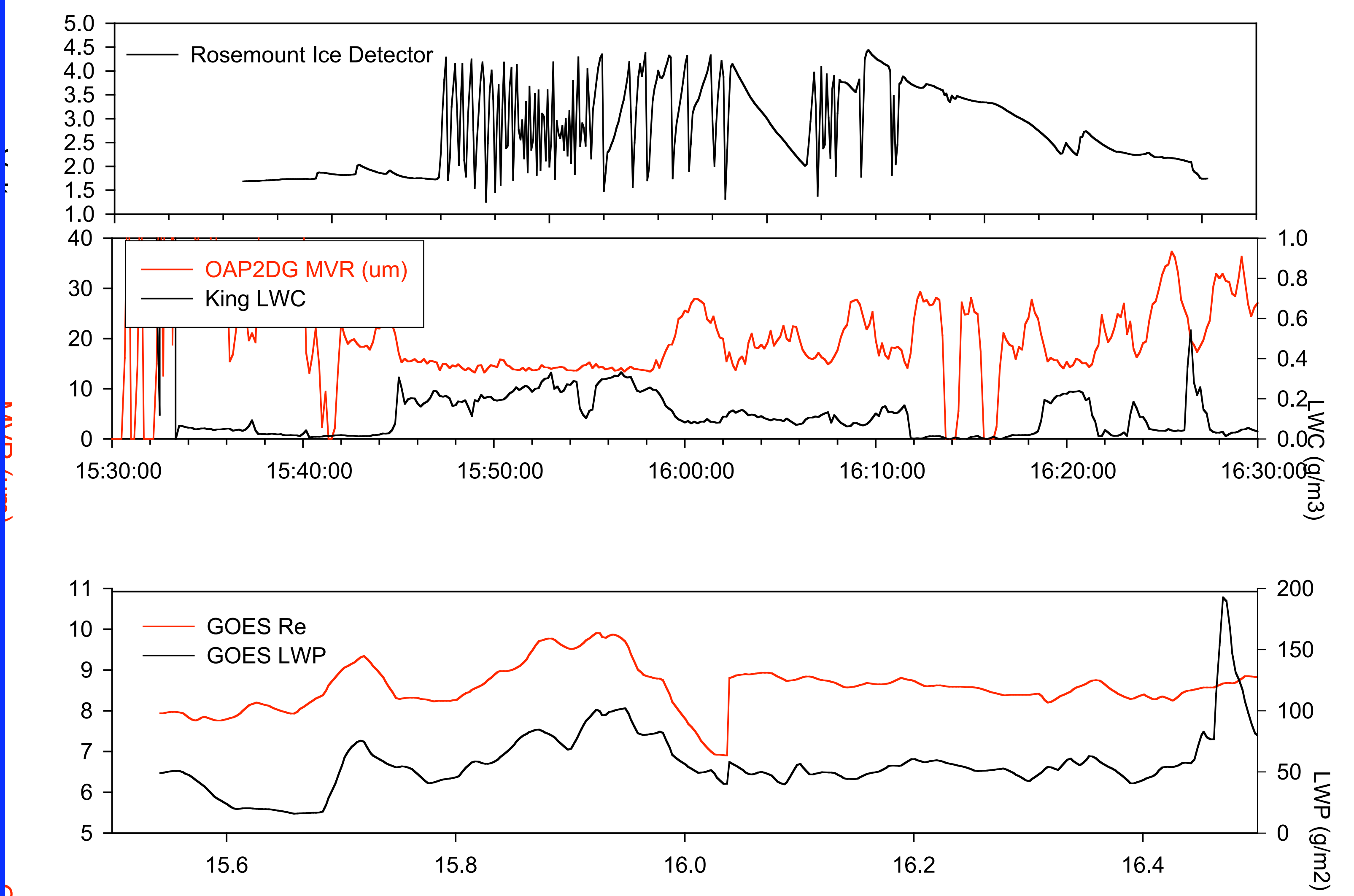
GOES Droplet Radius



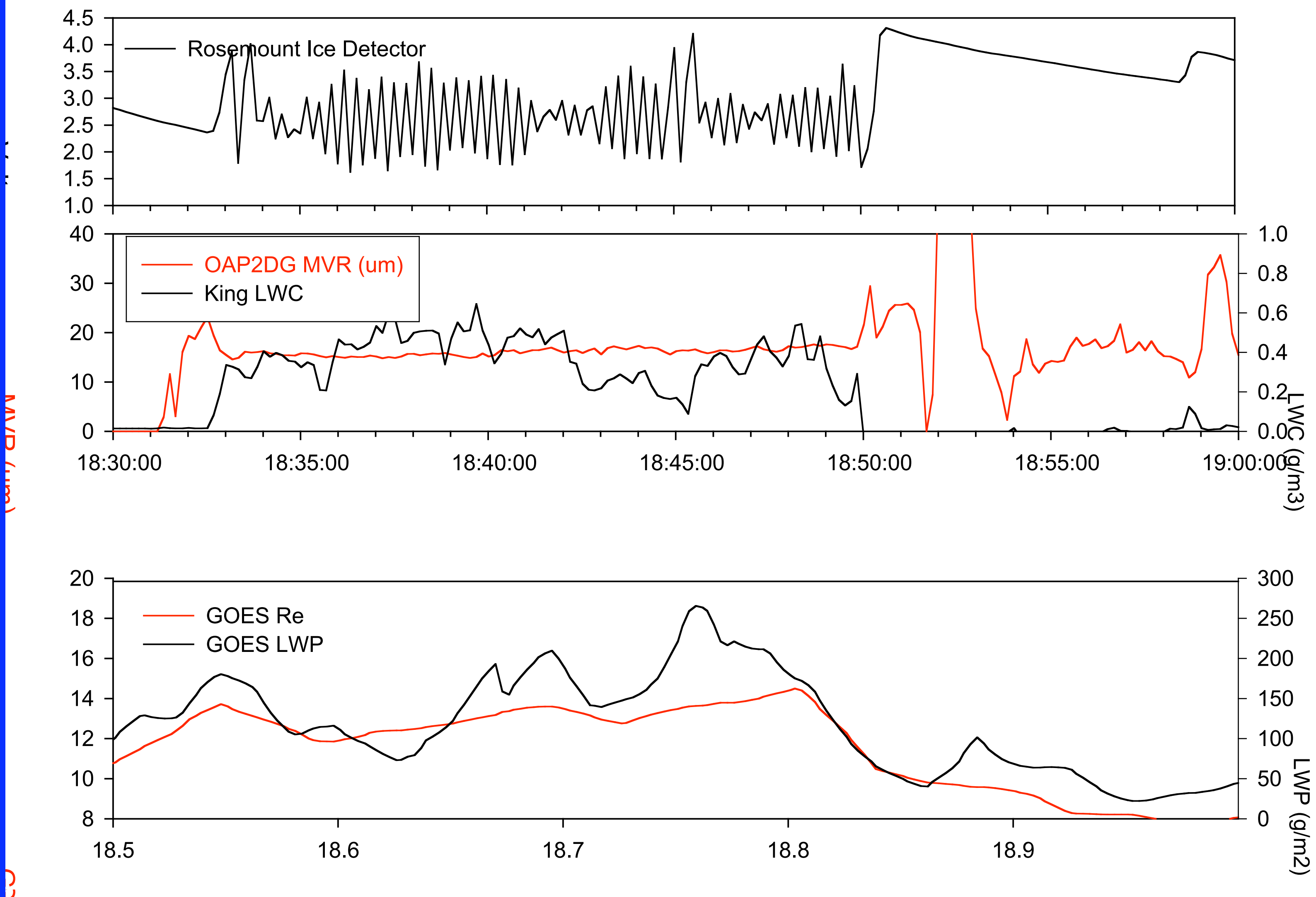
GOES Liquid Water Path



Satellite/Aircraft Comparison
March 5, 1998



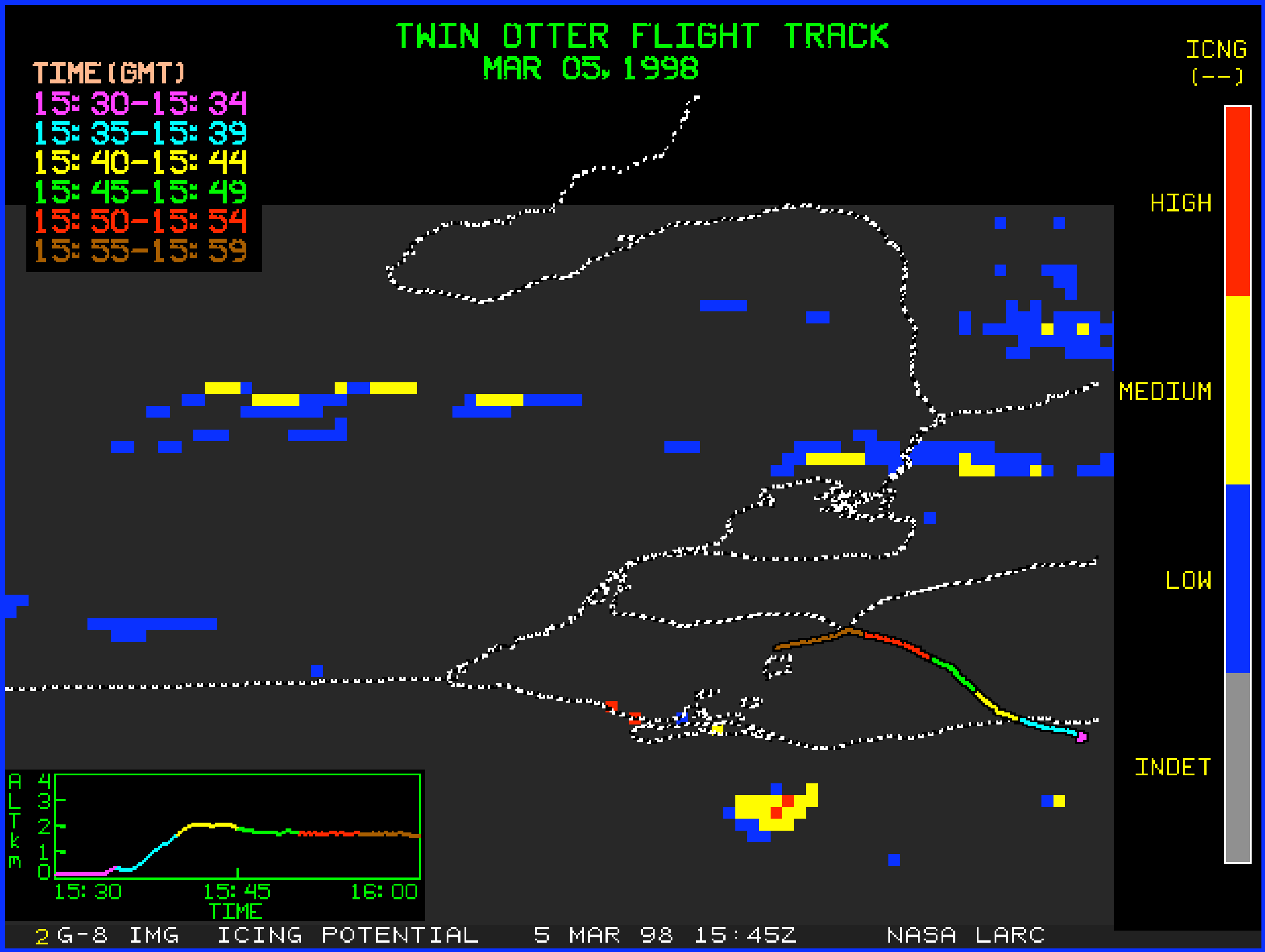
Satellite/Aircraft Comparison
March 5, 1998



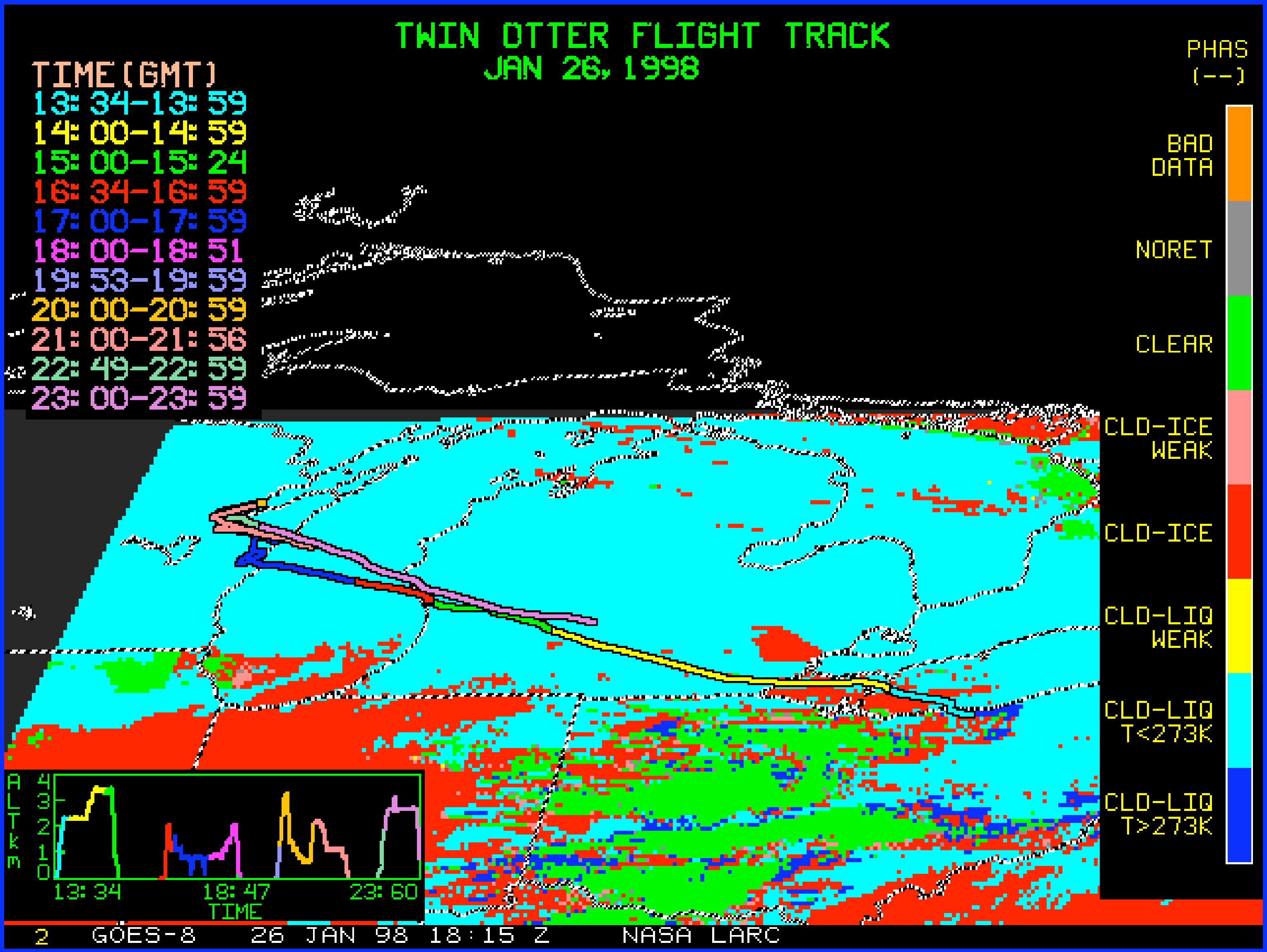
PROTOTYPE ICING CATEGORIES

value	Criteria			icing intensity
0	clear or water cloud (w/Tcld > 272 K or others) or	ice cloud w/OD < 8		no ice
1	ice cloud	optical depth > 8.0		indeterminate
2	re > 11 μm	LWP > 100	Tcld < 272 K	low
3	re > 11 μm	LWP > 200	Tcld < 272 K	mid
4	re > 11 μm	LWP > 300	Tcld < 272 K	high
5	re > 9 μm	LWP > 400	Tcld < 272 K	low
6	re > 9 μm	LWP > 500	Tcld < 272 K	mid
7	re > 11 μm	LWP > 300	Tcld < 253 K	high
8	re > 9 μm	LWP > 400,	Tcld < 253 K	high

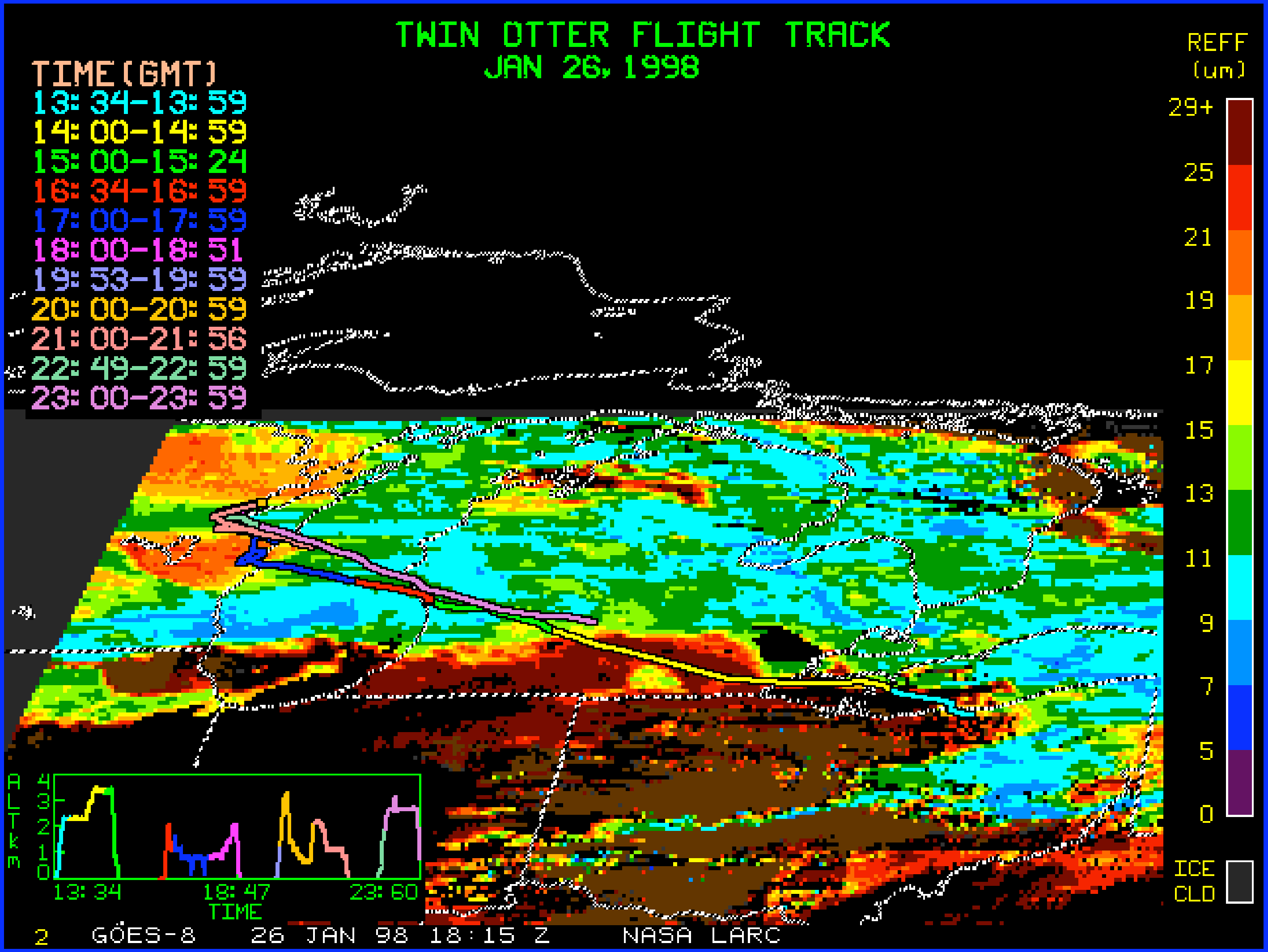
GOES ICING



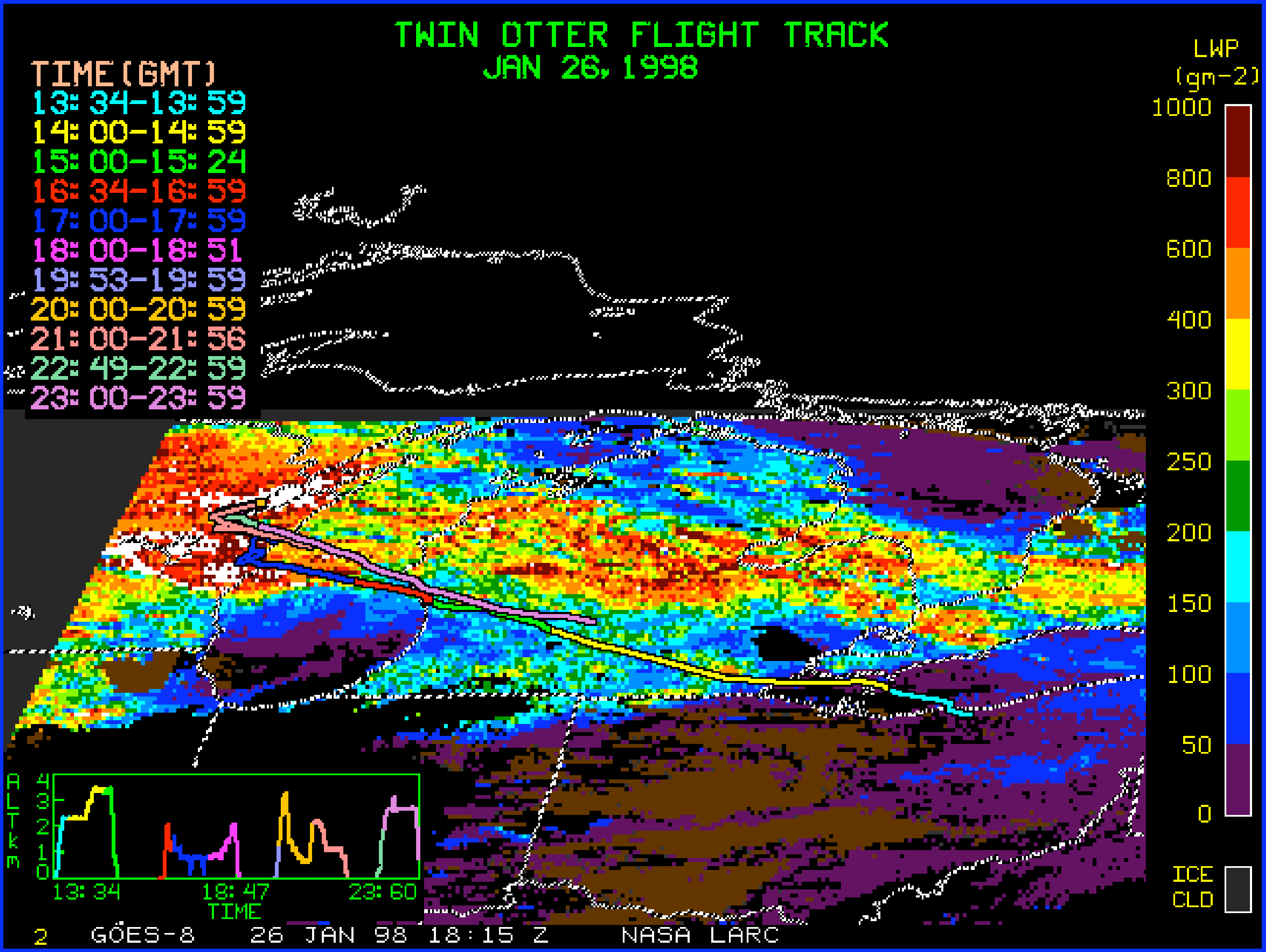
TWIN OTTER FLIGHT TRACK
MAR 05, 1998
TIME(GMT)
15:30-15:34
15:35-15:39
15:40-15:44
15:45-15:49
15:50-15:54
15:55-15:59
ICNG
(--)
HIGH
MEDIUM
LOW
INDET
ALT km
0
1
2
3
4
15:30
15:45
16:00
TIME
2 G-8 IMG ICING POTENTIAL 5 MAR 98 15:45Z NASA LARC


TWIN OTTER FLIGHT TRACK
JAN 26, 1998
TIME(GMT)
13:34-13:59
14:00-14:59
15:00-15:24
16:34-16:59
17:00-17:59
18:00-18:51
19:53-19:59
20:00-20:59
21:00-21:56
22:49-22:59
23:00-23:59
PHAS
(--)
BAD DATA
NORET
CLEAR
CLD-ICE WEAK
CLD-ICE
CLD-LIQ WEAK
CLD-LIQ T<273K
CLD-LIQ T>273K
ALT km
4
3
2
1
0
13:34
18:47
23:60
TIME
2 GOES-8 26 JAN 98 18:15 Z NASA LARC

GOES Droplet Radius

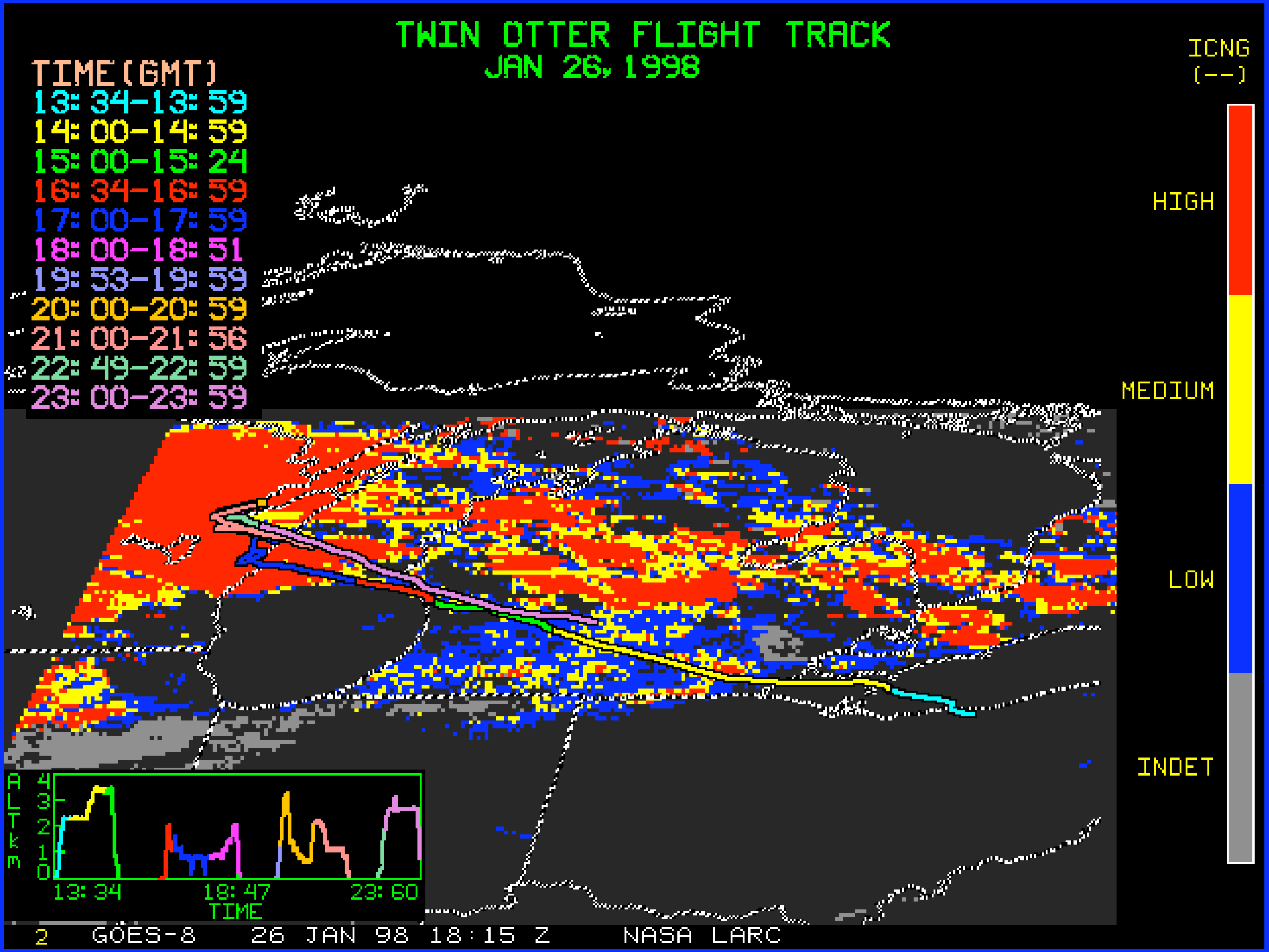


GOES LWP

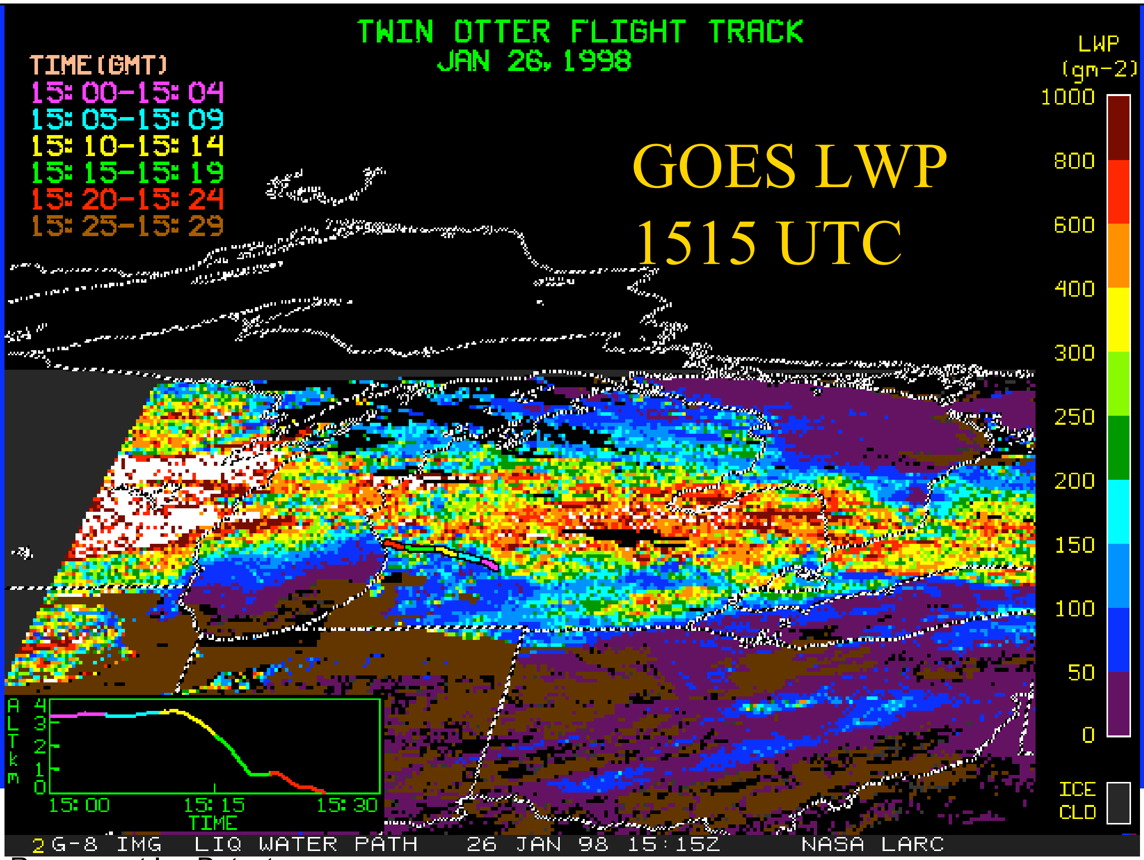


TWIN OTTER FLIGHT TRACK
JAN 26, 1998
TIME(GMT)
13:34-13:59
14:00-14:59
15:00-15:24
16:34-16:59
17:00-17:59
18:00-18:51
19:53-19:59
20:00-20:59
21:00-21:56
22:49-22:59
23:00-23:59
LWP
(gm-2)
1000
800
600
400
300
250
200
150
100
50
0
ICE
CLD
ALT km
4
3
2
1
0
13:34
18:47
23:60
TIME
2 GOES-8 26 JAN 98 18:15 Z NASA LARC

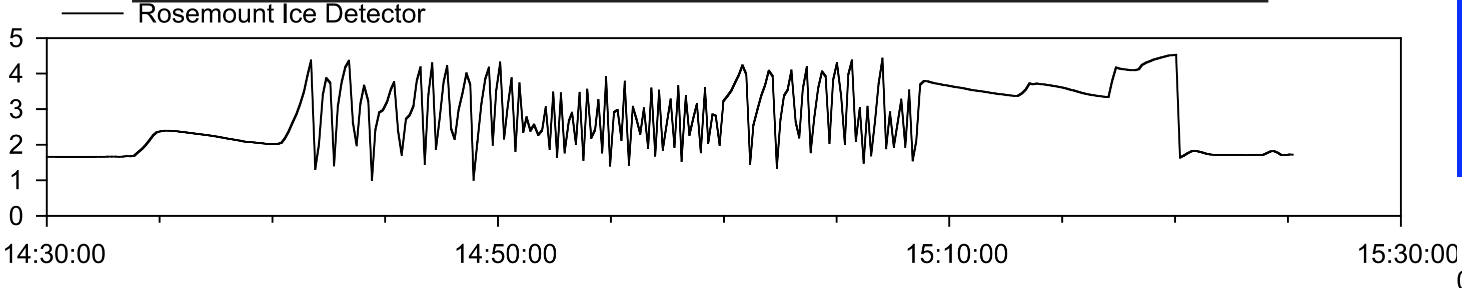
GOES ICING



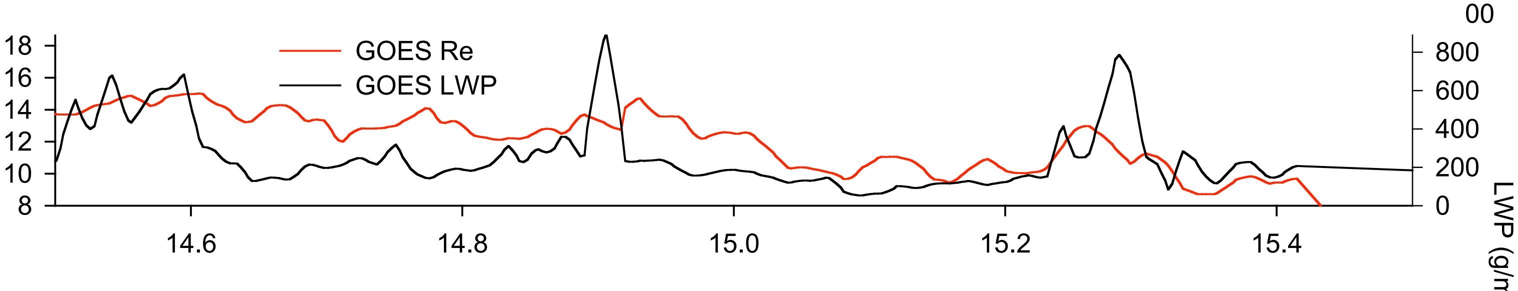
TWIN OTTER FLIGHT TRACK
JAN 26, 1998
TIME(GMT)
13:34-13:59
14:00-14:59
15:00-15:24
16:34-16:59
17:00-17:59
18:00-18:51
19:53-19:59
20:00-20:59
21:00-21:56
22:49-22:59
23:00-23:59
ICNG
(--)
HIGH
MEDIUM
LOW
INDET
A L T k m
4
3
2
1
0
13:34
18:47
23:60
TIME
2 GOES-8 26 JAN 98 18:15 Z NASA LARC



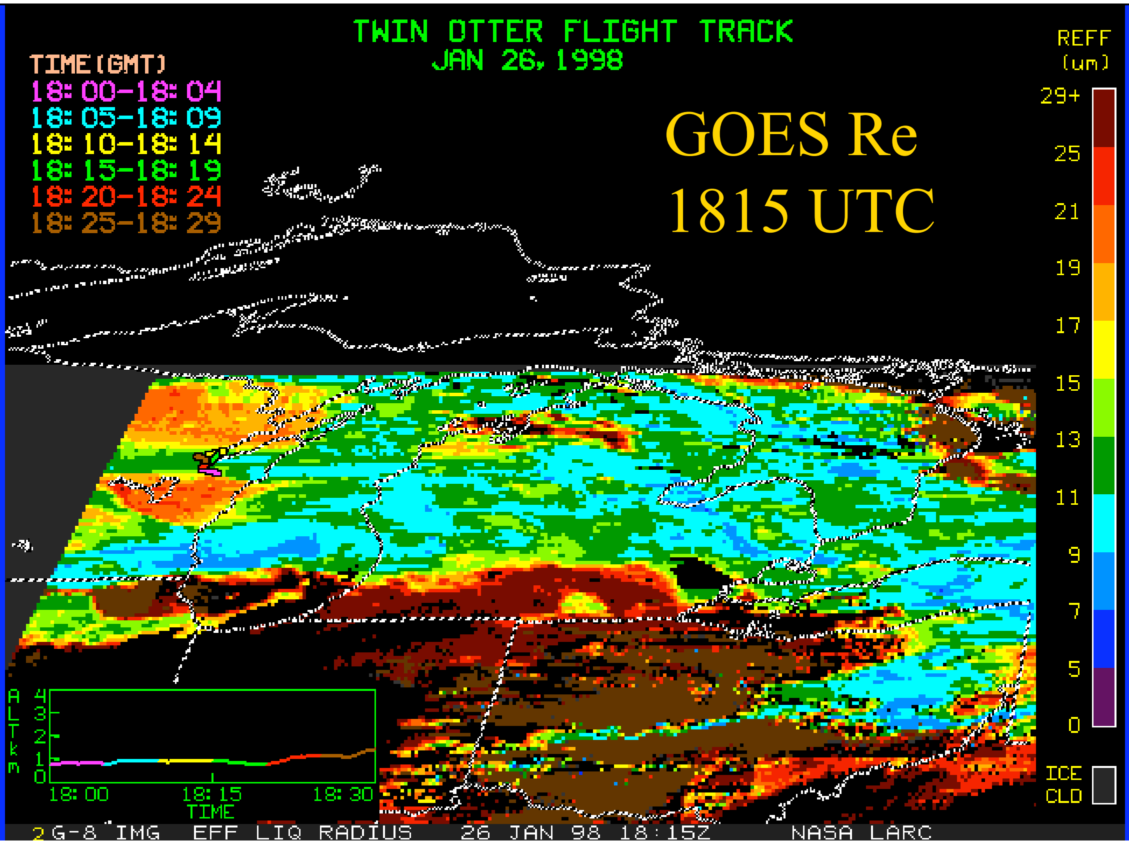
TWIN OTTER FLIGHT TRACK
JAN 26, 1998
TIME (GMT)
15:00-15:04
15:05-15:09
15:10-15:14
15:15-15:19
15:20-15:24
15:25-15:29
GOES LWP
1515 UTC
LWP (gm-2)
1000
800
600
400
300
250
200
150
100
50
0
ICE CLD
ALT km
15:00
15:15
15:30
TIME
2 G-8 IMG LIQ WATER PATH 26 JAN 98 15:15Z NASA LARC

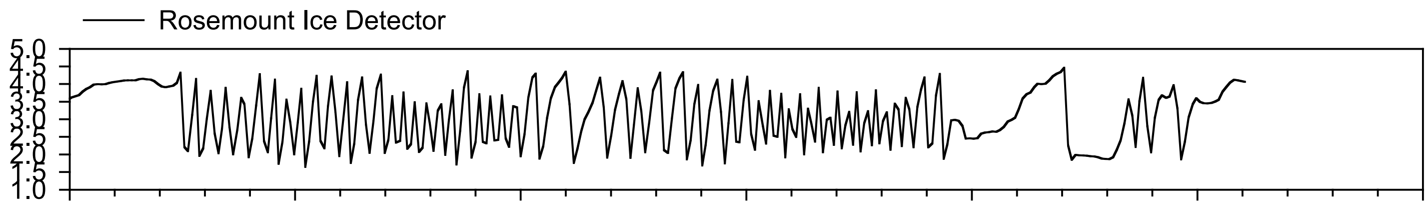


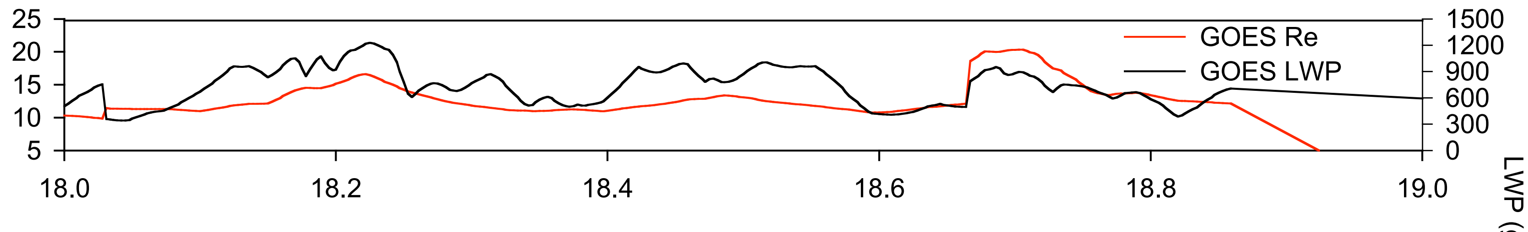
Rosemount Ice Detector
14:30:00
14:50:00
15:10:00
15:30:00



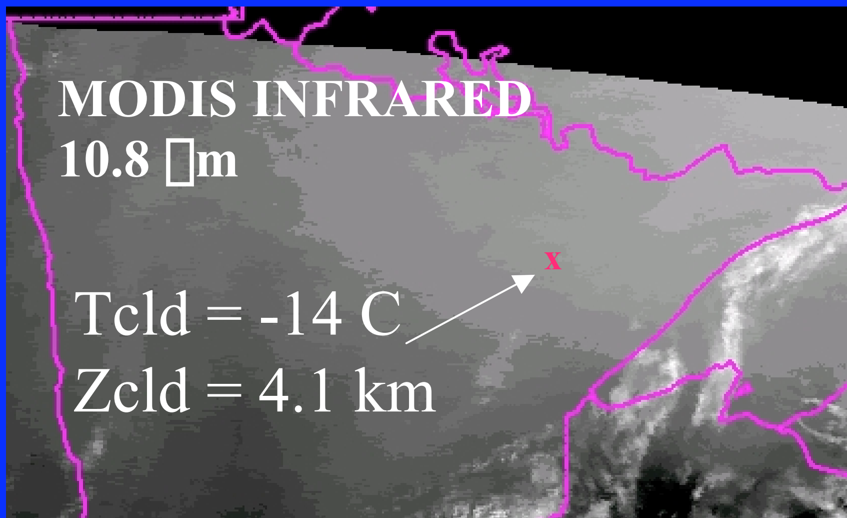
GOES Re
GOES LWP
14.6
14.8
15.0
15.2
15.4
LWP (g/m

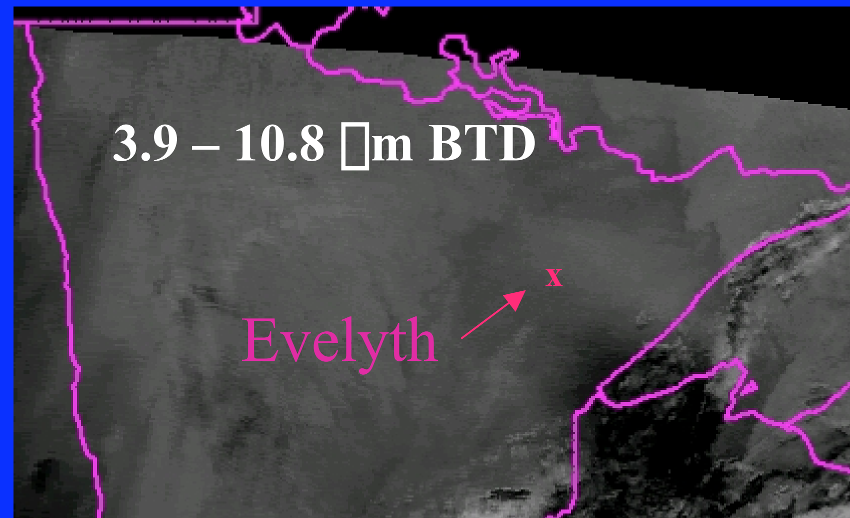

TWIN OTTER FLIGHT TRACK
JAN 26, 1998
TIME (GMT)
18:00-18:04
18:05-18:09
18:10-18:14
18:15-18:19
18:20-18:24
18:25-18:29
GOES Re
1815 UTC
REFF (um)
29+
25
21
19
17
15
13
11
9
7
5
0
ICE CLD
ALT km
18:00
18:15
18:30
TIME
G-8 IMG EFF LIQ RADIUS 26 JAN 98 18:15Z NASA LARC

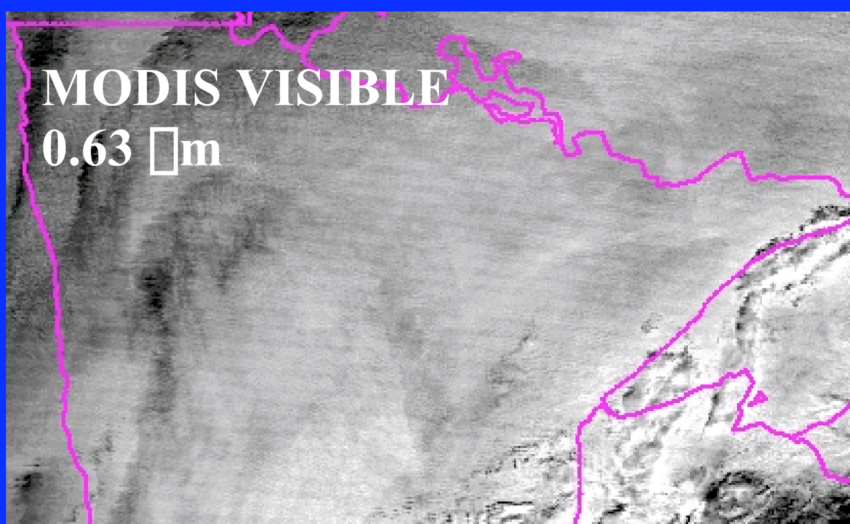

Rosemount Ice Detector
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0

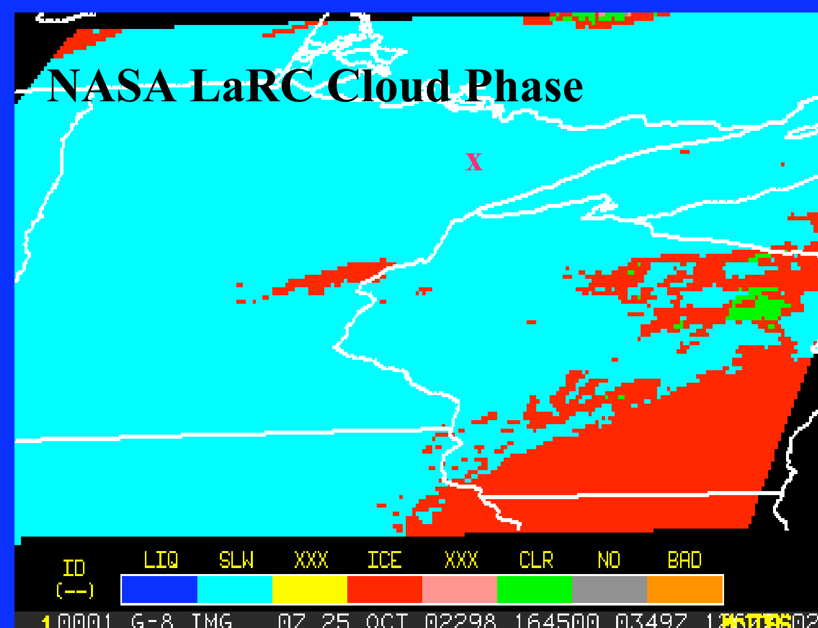

GOES Re
GOES LWP
25
20
15
10
5
1500
1200
900
600
300
0
18.0
18.2
18.4
18.6
18.8
19.0

Evelyth, Minn. King Air Crash
Oct 25, 2002 at 1645 UTC

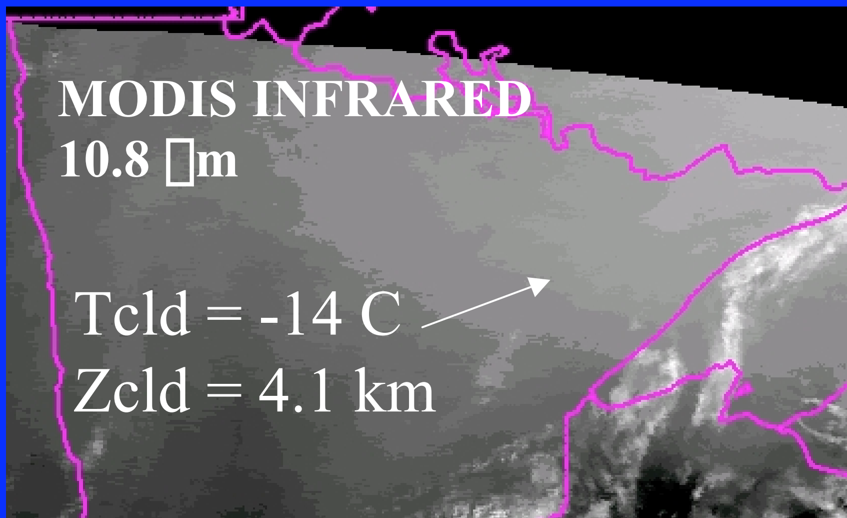


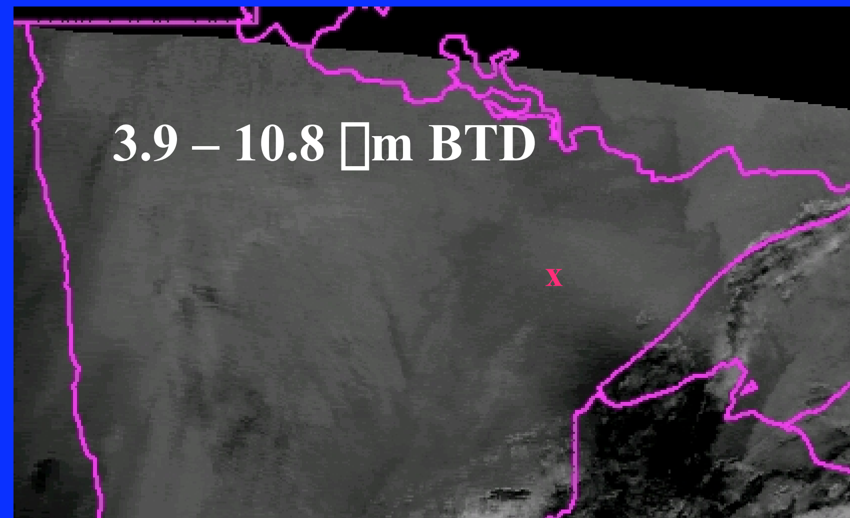


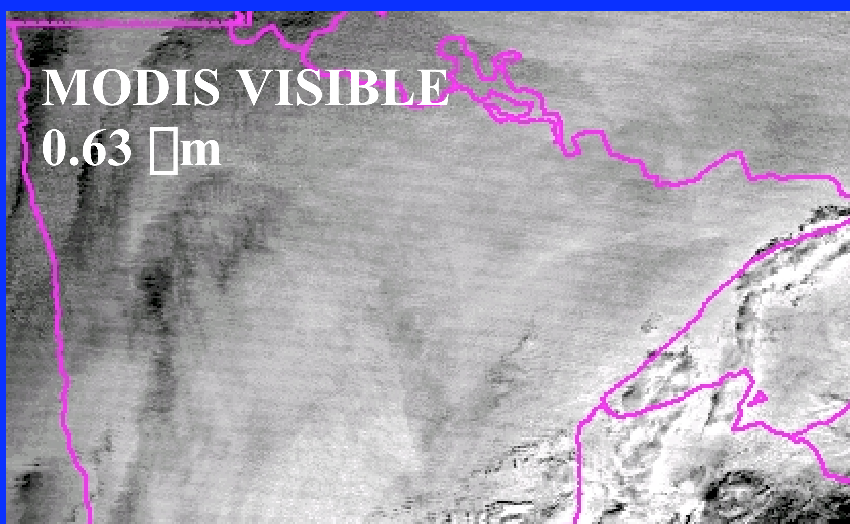




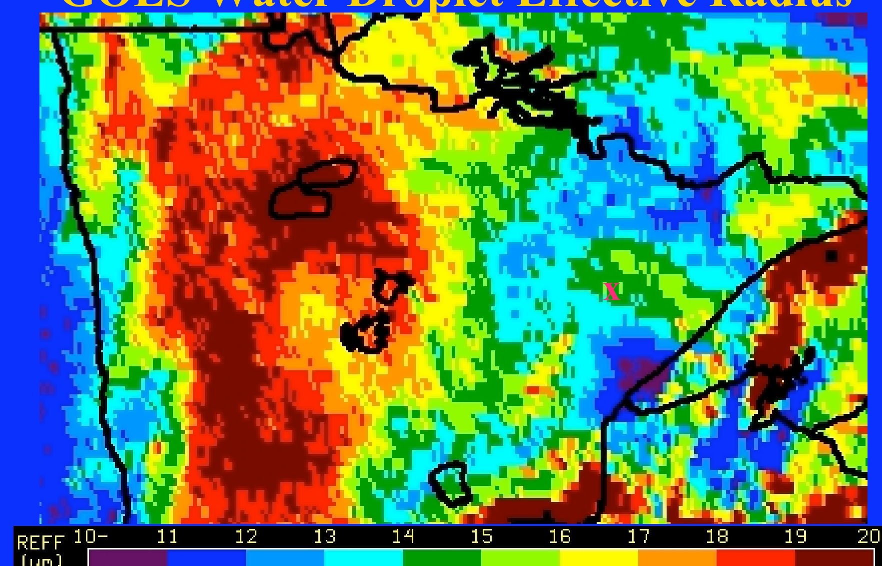
Evelyth, Minn. King Air Crash
Oct 25, 2002 at 1645 UTC







GOES Water Droplet Effective Radius

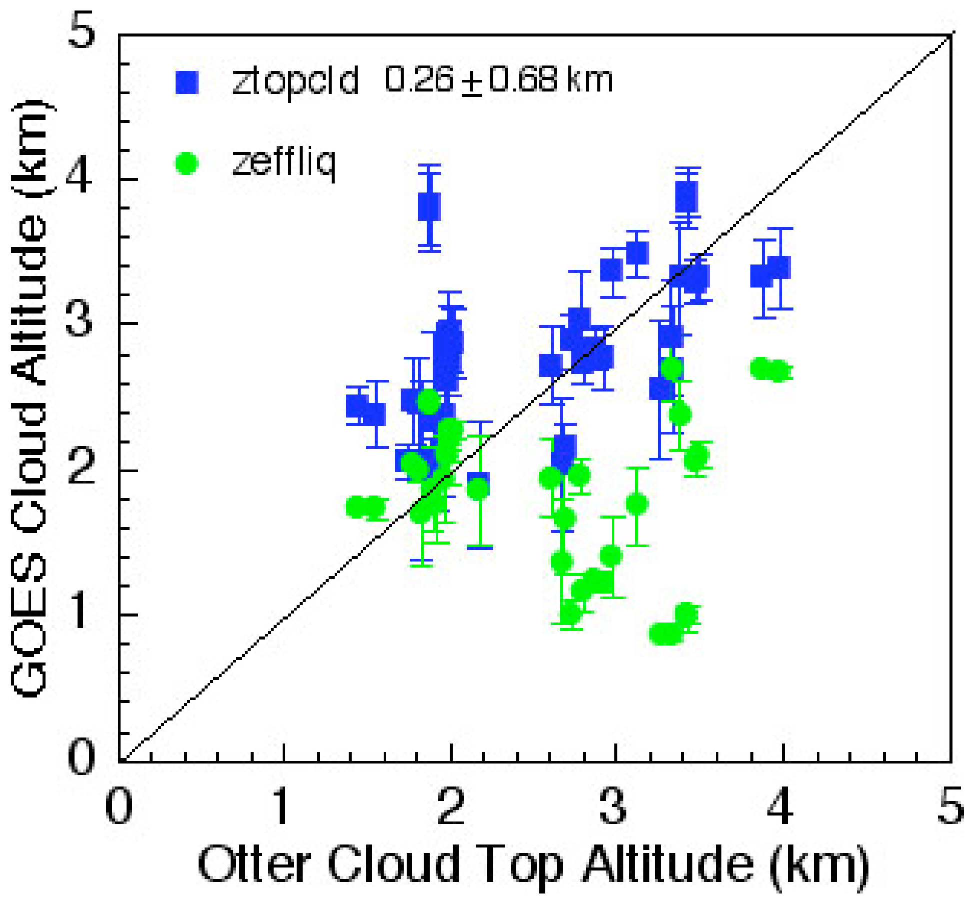


Cloud Height Comparisons 1997-98

Twin Otter Icing Flights vs GOES Lapse Rate Method

ztopcld = estimated height of all cloud in view

zeffliq = estimated height of liquid clouds only



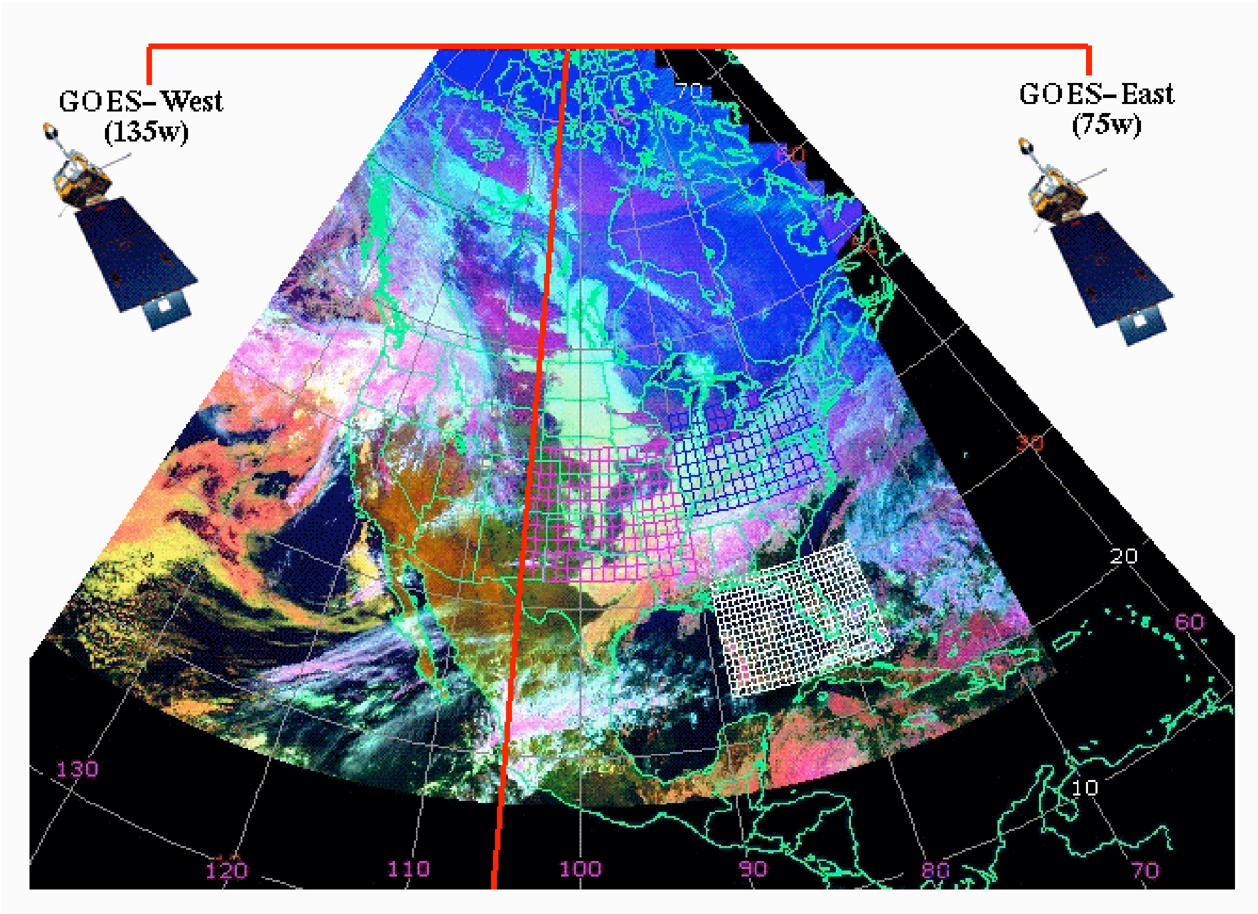
WEB-BASED SATELLITE SUPPORT FOR FIELD PROGRAMS

- Evolving web page satellite product, forecast support for field programs
  - history starting with NASA FIRE experiments
  - real time imagery in ARM field experiments
  - satellite overpass & viewing conditions in INCA (2001)
  - real time satellite imagery, cloud products, etc. in CRYSTAL-FACE 2002
  - supported THORPEX and will support again this fall

- Real time satellite ingests via MCIDA, archived& gifs on web (other sats when req'd)
  - GOES E/W
  - AVHRR
  - Terra/Aqua MODIS
- Real time model reanalyses/forecasts & surface data via MCIDAS

COMBINING GOES-EAST & WEST FOR CONUS DOMAIN

Proposed domain: 25°N - 50°N; 50°W - 130°W



EXPANSION PROCESS

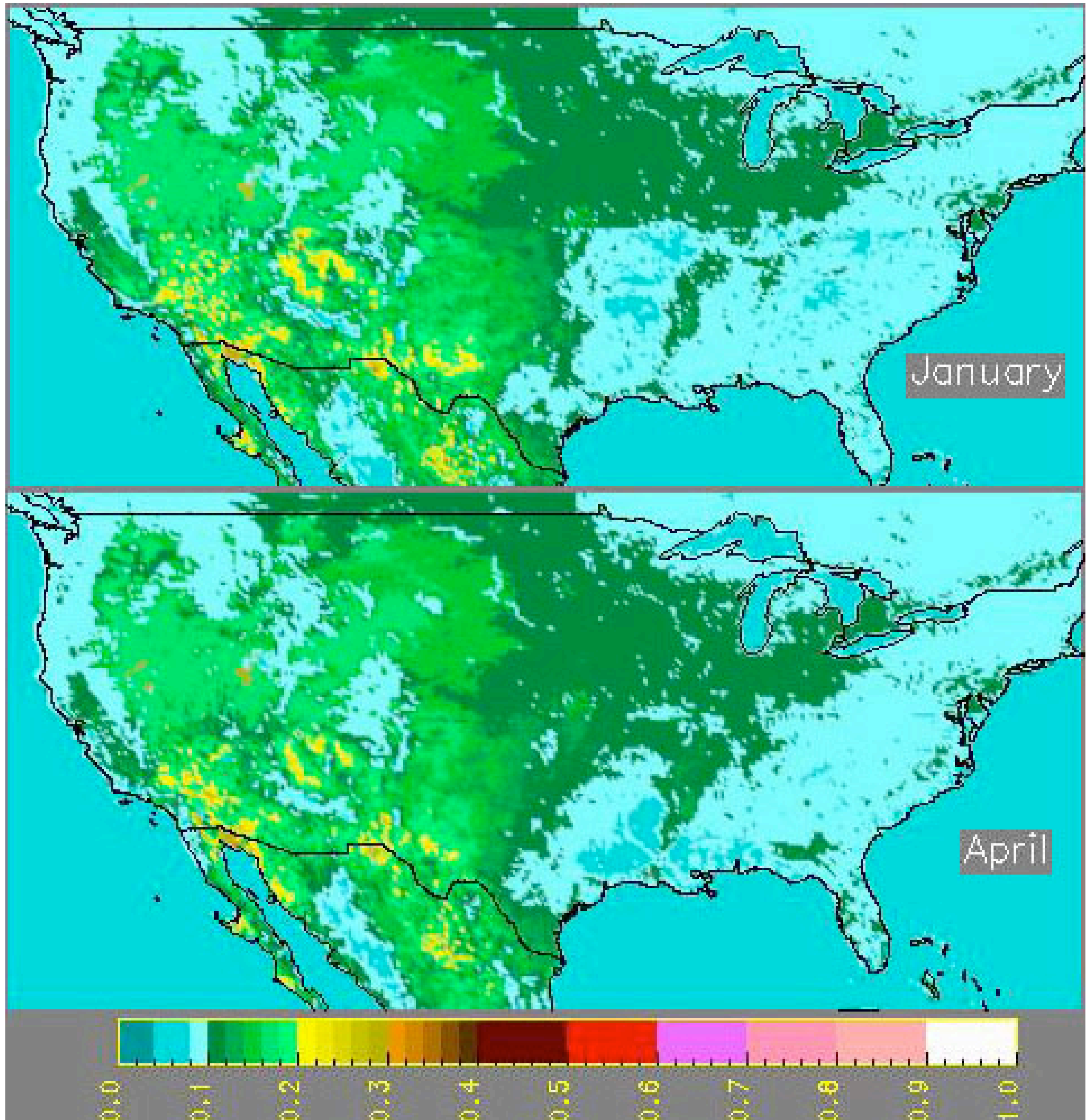
- **Focus on GOES-East (50°W - 105°W)**
  - **Develop ingest system for model & satellite input**
  - **Size the problem for computer processing**
  - **Provide products online (graphical & digital)**
  - **Make alterations for new channel (13.5 μm)**

- **Focus on GOES-West (105°W - 135°W)**
  - **Intercalibrate east & west**
  - **Develop ingest system**
  - **Combine results with East for seamless product**

Initial Clear-sky Visible (0.65 μm) Albedos for CONUS Cloud Analysis

Overhead Sun Values Derived From 1998 VIRS Data by CERES Project

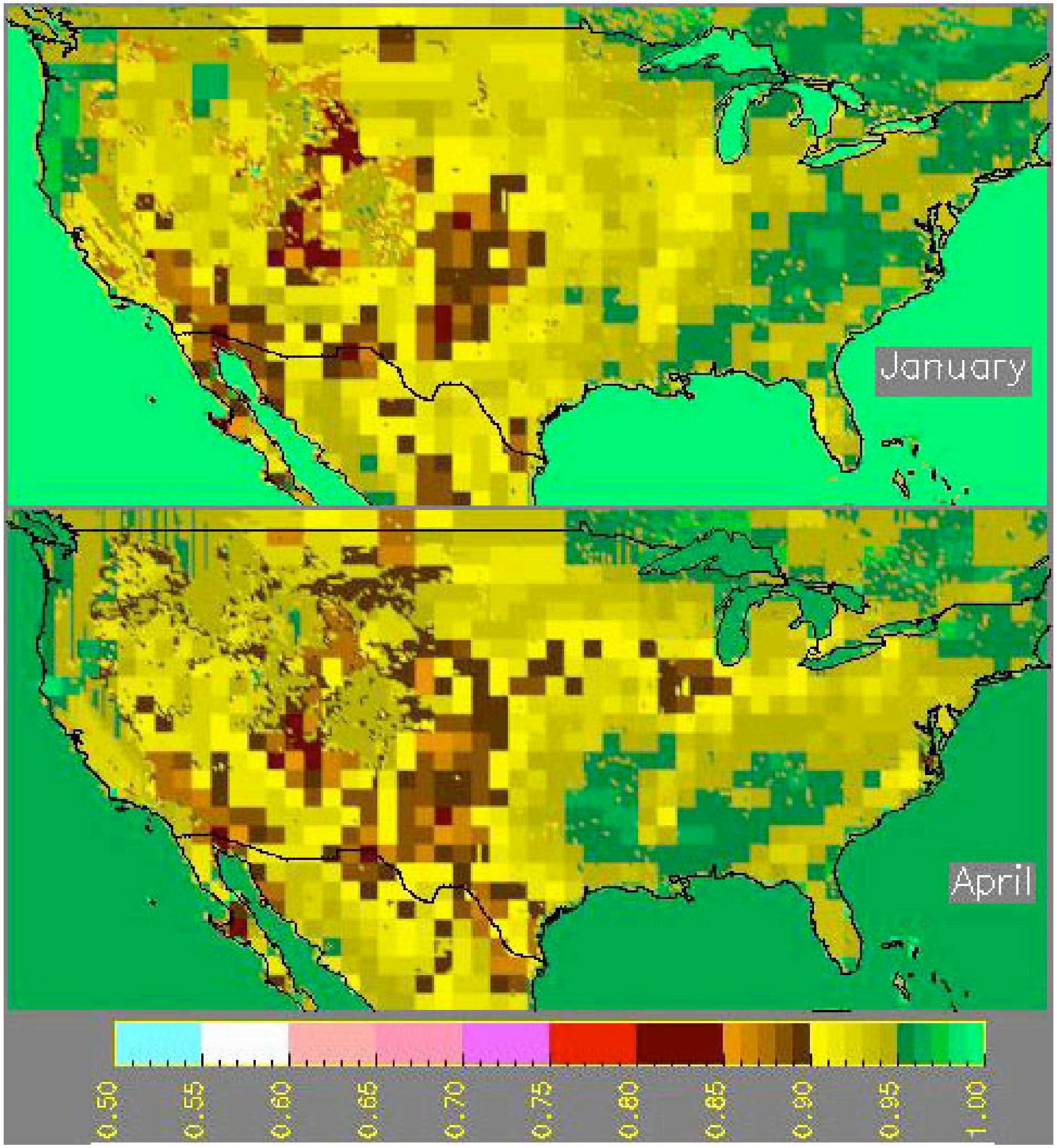
GOES Visible Channels Have Slightly Different Wavelengths Requiring Refinement for Future GOES Applications



Initial 3.7-μm Surface Emissivities for CONUS Cloud Analysis

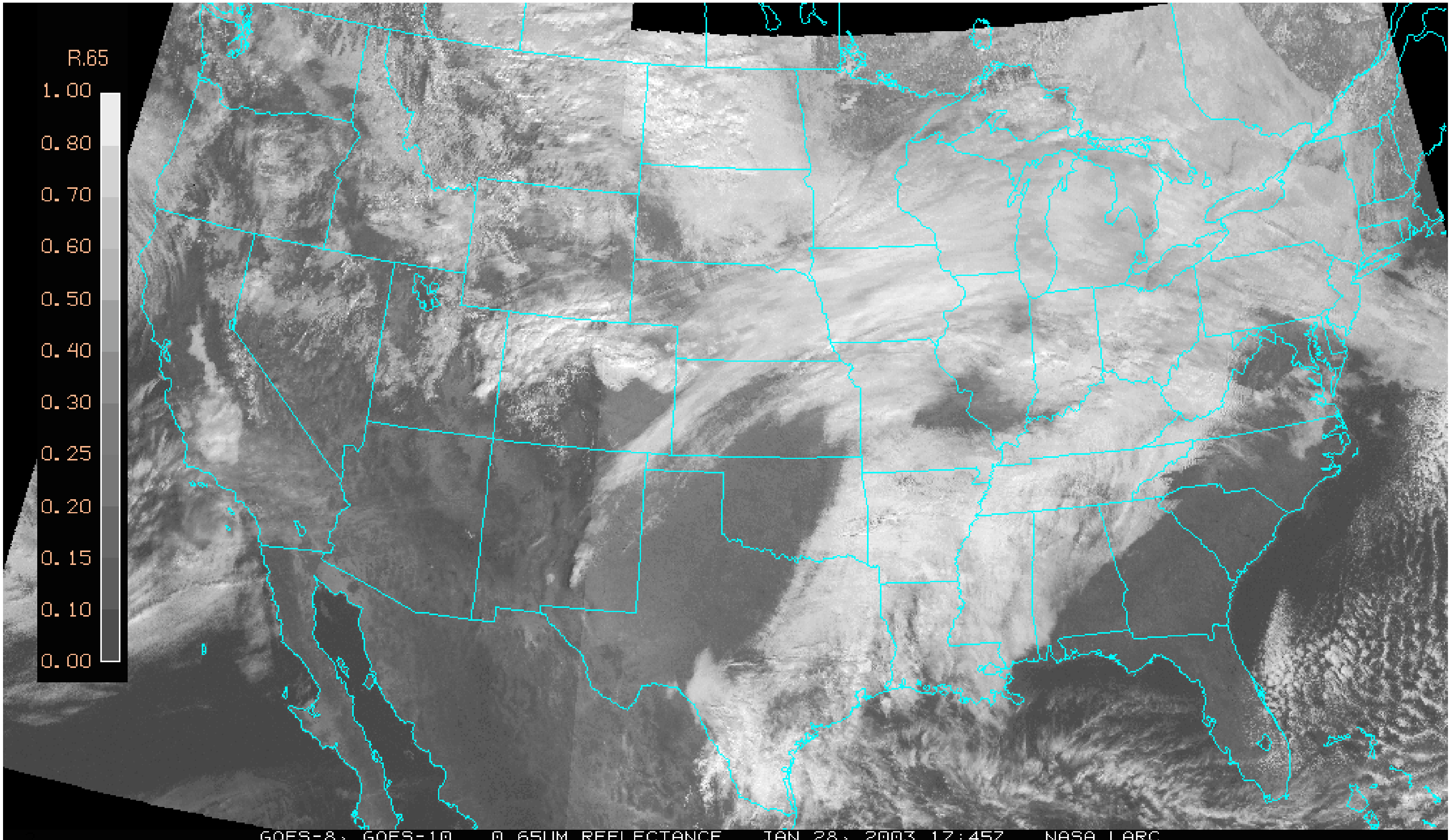
Derived From AVHRR Data by CERES Project

GOES Solar Infrared Channel Has Different Wavelength (3.9 μm) Requiring Refinement for Future GOES Applications



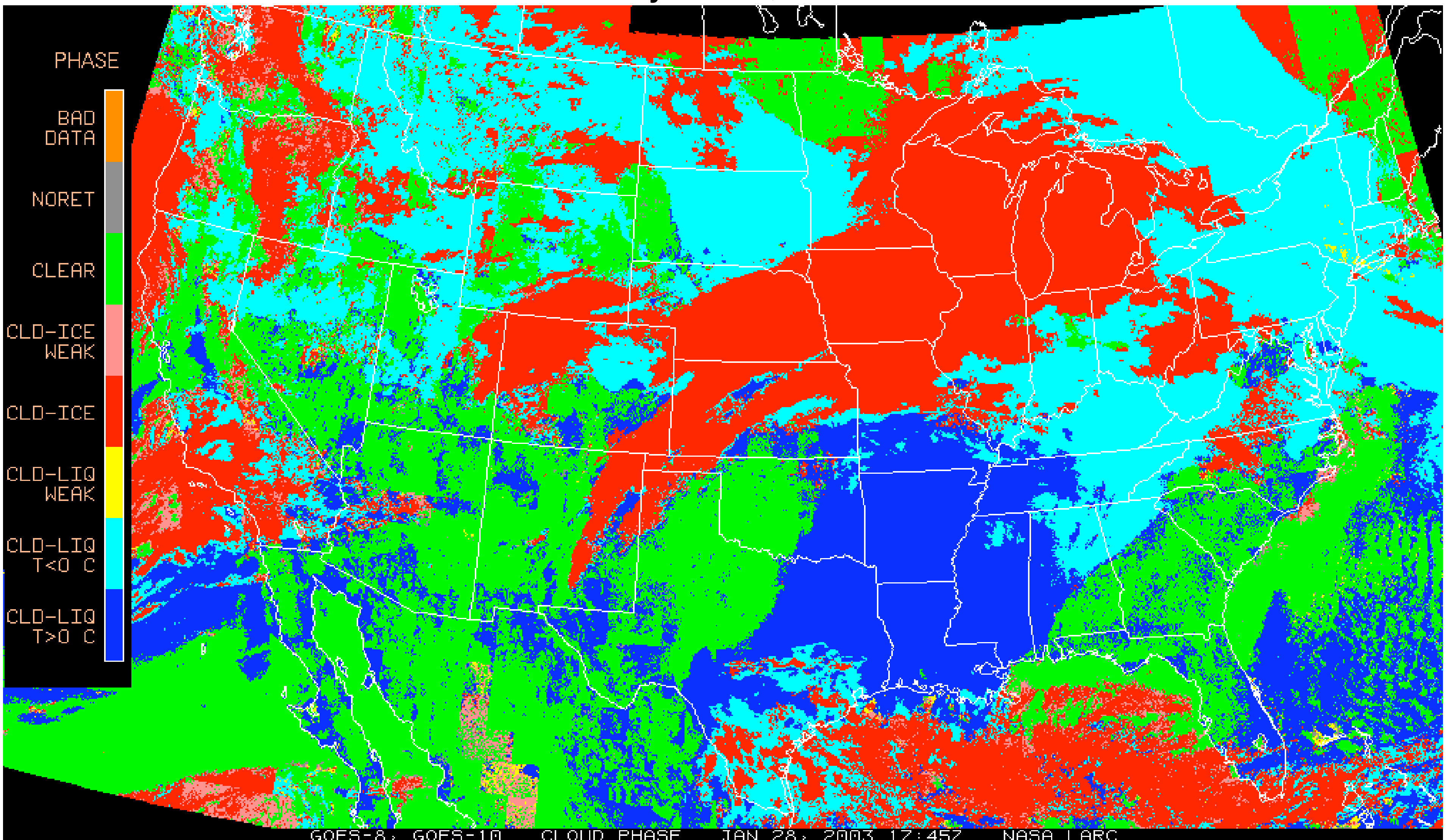
Combined GOES-8 & GOES-10 CONUS Imagery

Visible Channel, 28 January 2003, 1745 UTC



Combined GOES-8 & GOES-10 CONUS Cloud Mask

28 January 2003, 1745 UTC

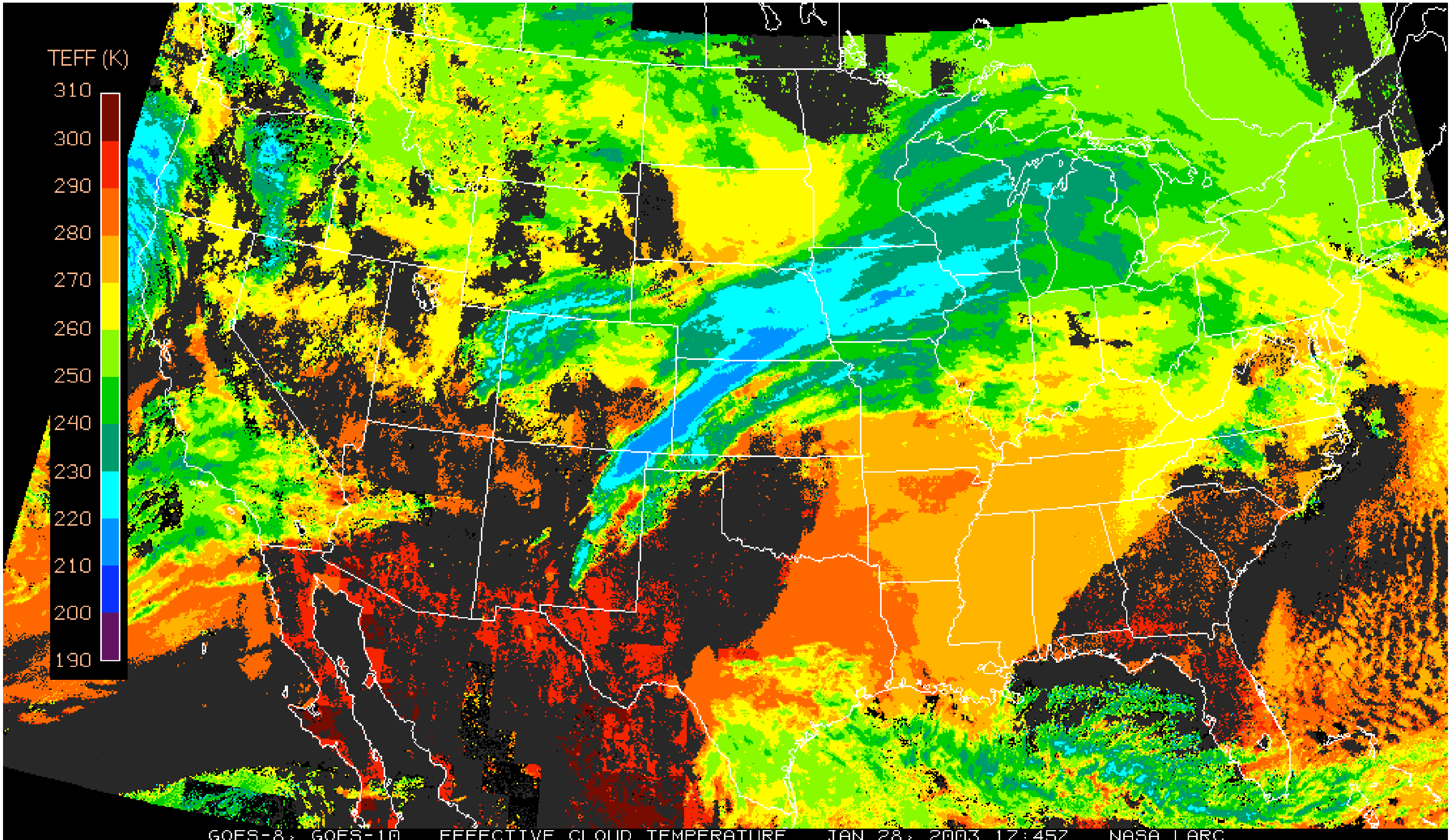


NASA Langley Research Center / Atmospheric Sciences

Icing Remote Sensing Meeting, Boulder, CO, September 16-17, 2003

Combined GOES-8 & GOES-10 CONUS Cloud Temperature

28 January 2003, 1745 UTC

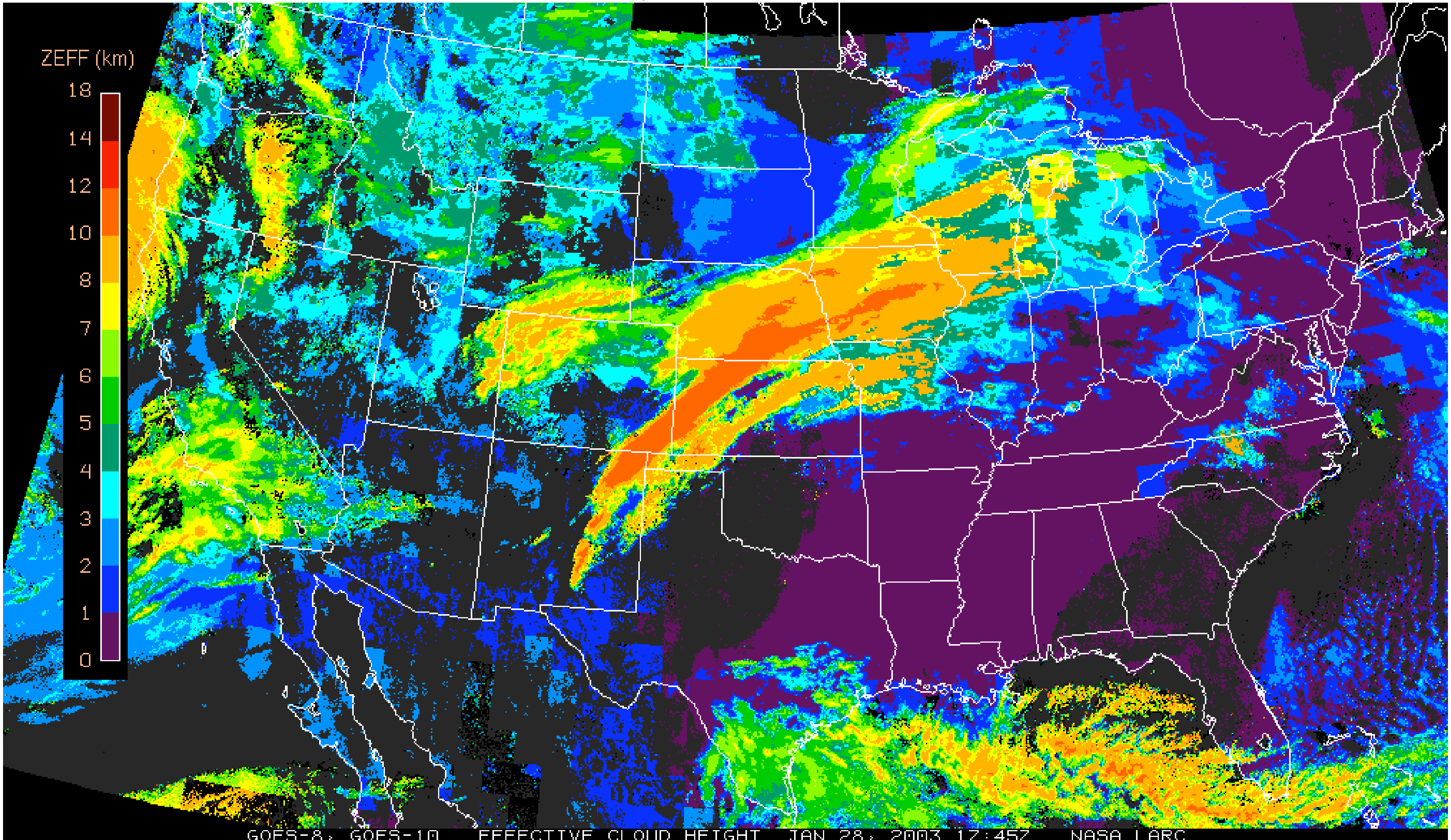


NASA Langley Research Center / Atmospheric Sciences

Icing Remote Sensing Meeting, Boulder, CO, September 16-17, 2003

Combined GOES-8 & GOES-10 CONUS Cloud Top Altitude

28 January 2003, 1745 UTC

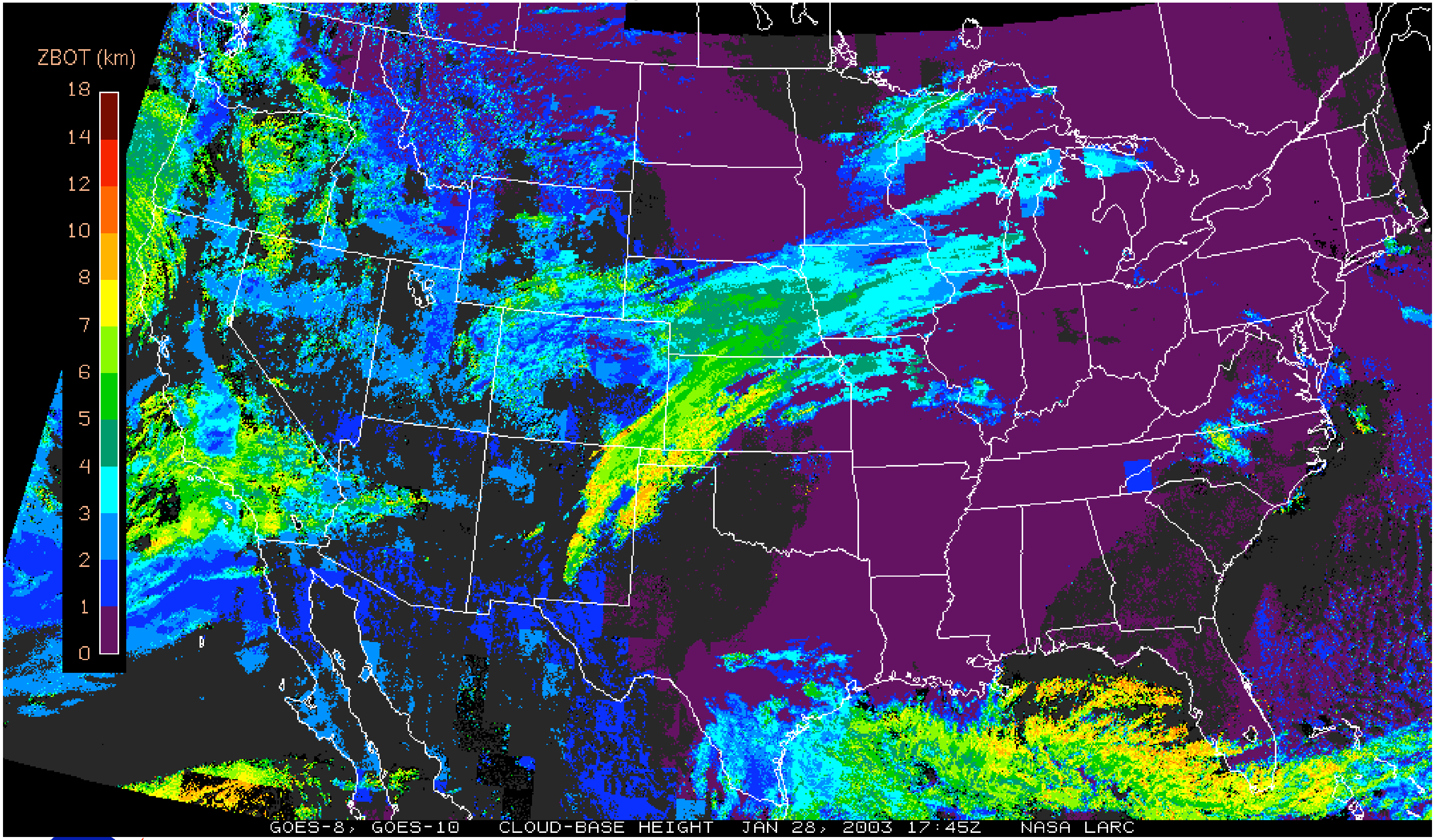


NASA Langley Research Center / Atmospheric Sciences

Icing Remote Sensing Meeting, Boulder, CO, September 16-17, 2003

Combined GOES-8 & GOES-10 CONUS Cloud Base Altitude

28 January 2003, 1745 UTC



NASA Langley Research Center / Atmospheric Sciences

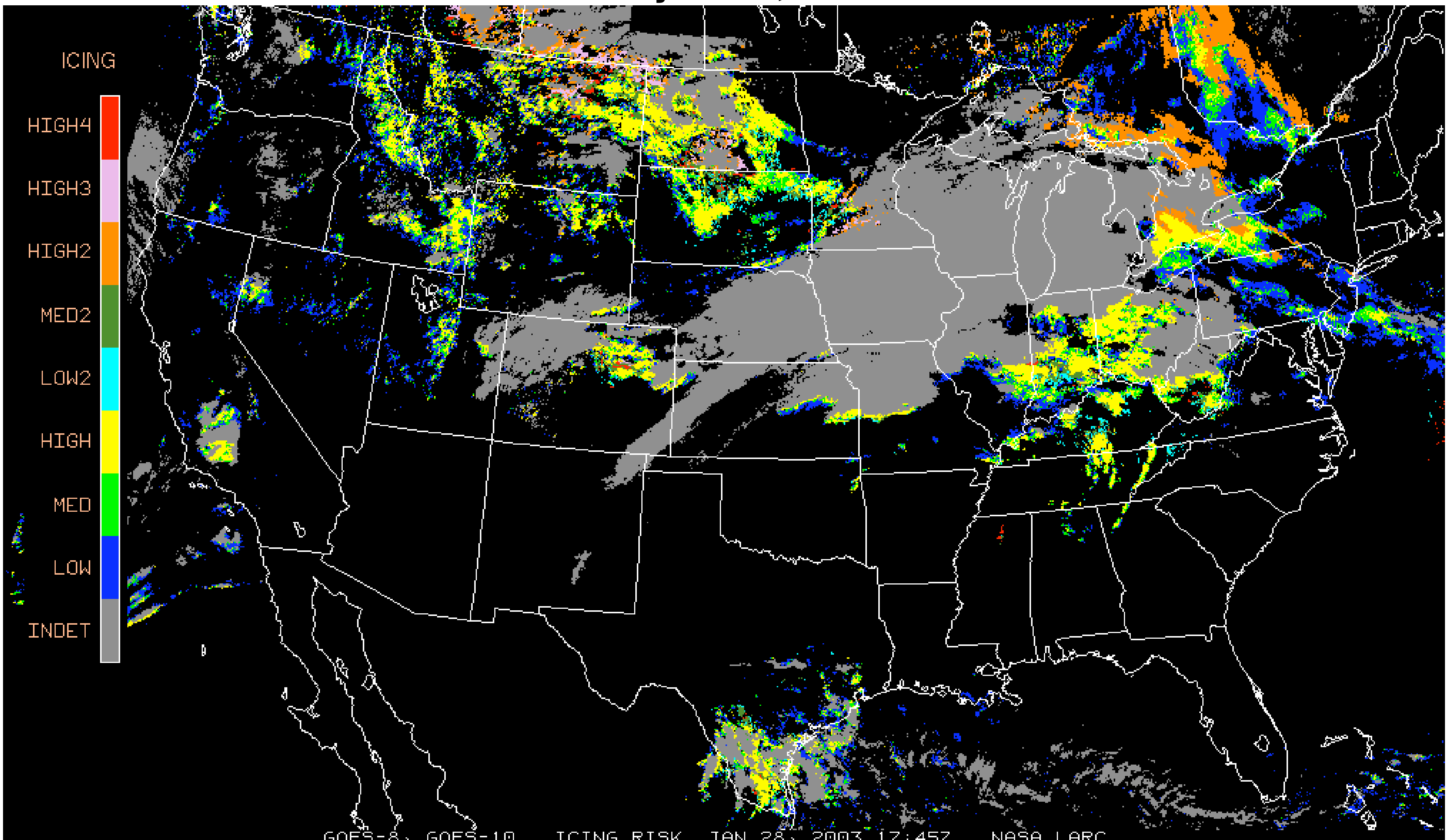
Icing Remote Sensing Meeting, Boulder, CO, September 16-17, 2003

PROTOTYPE ICING CATEGORIES

value	Criteria			icing intensity
0	clear or water cloud (w/Tcld > 272 K or others) or ice cloud w/OD < 8			no ice
1	ice cloud	optical depth > 8.0		indeterminate
2	re > 11 μm	LWP > 100	Tcld < 272 K	low
3	re > 11 μm	LWP > 200	Tcld < 272 K	mid
4	re > 11 μm	LWP > 300	Tcld < 272 K	high
5	re > 9 μm	LWP > 400	Tcld < 272 K	low
6	re > 9 μm	LWP > 500	Tcld < 272 K	mid
7	re > 11 μm	LWP > 300	Tcld < 253 K	high
8	re > 9 μm	LWP > 400,	Tcld < 253 K	high

Combined GOES-8 & GOES-10 CONUS Icing Category PROTOTYPE

28 January 2003, 1745 UTC

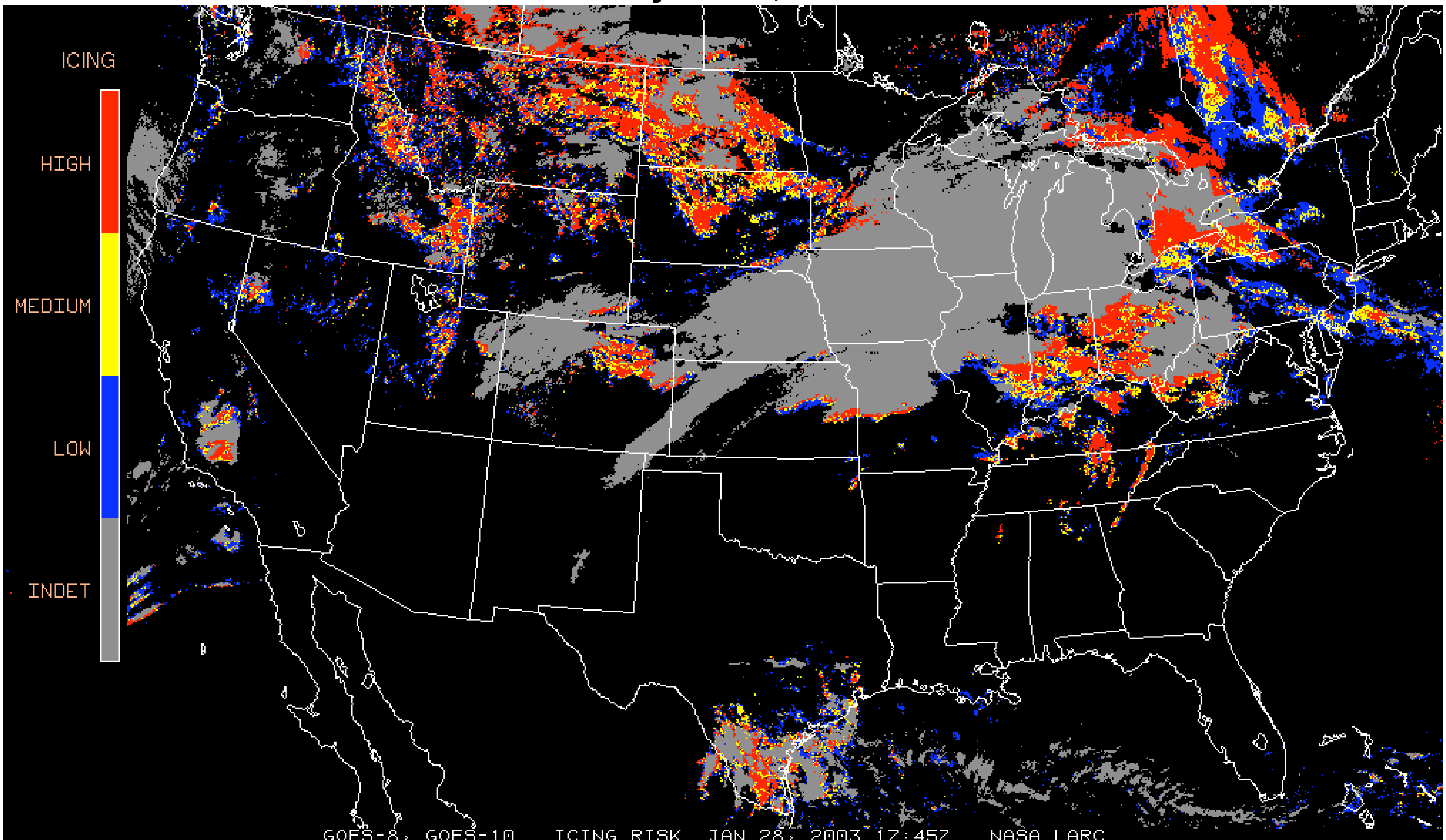


NASA Langley Research Center / Atmospheric Sciences

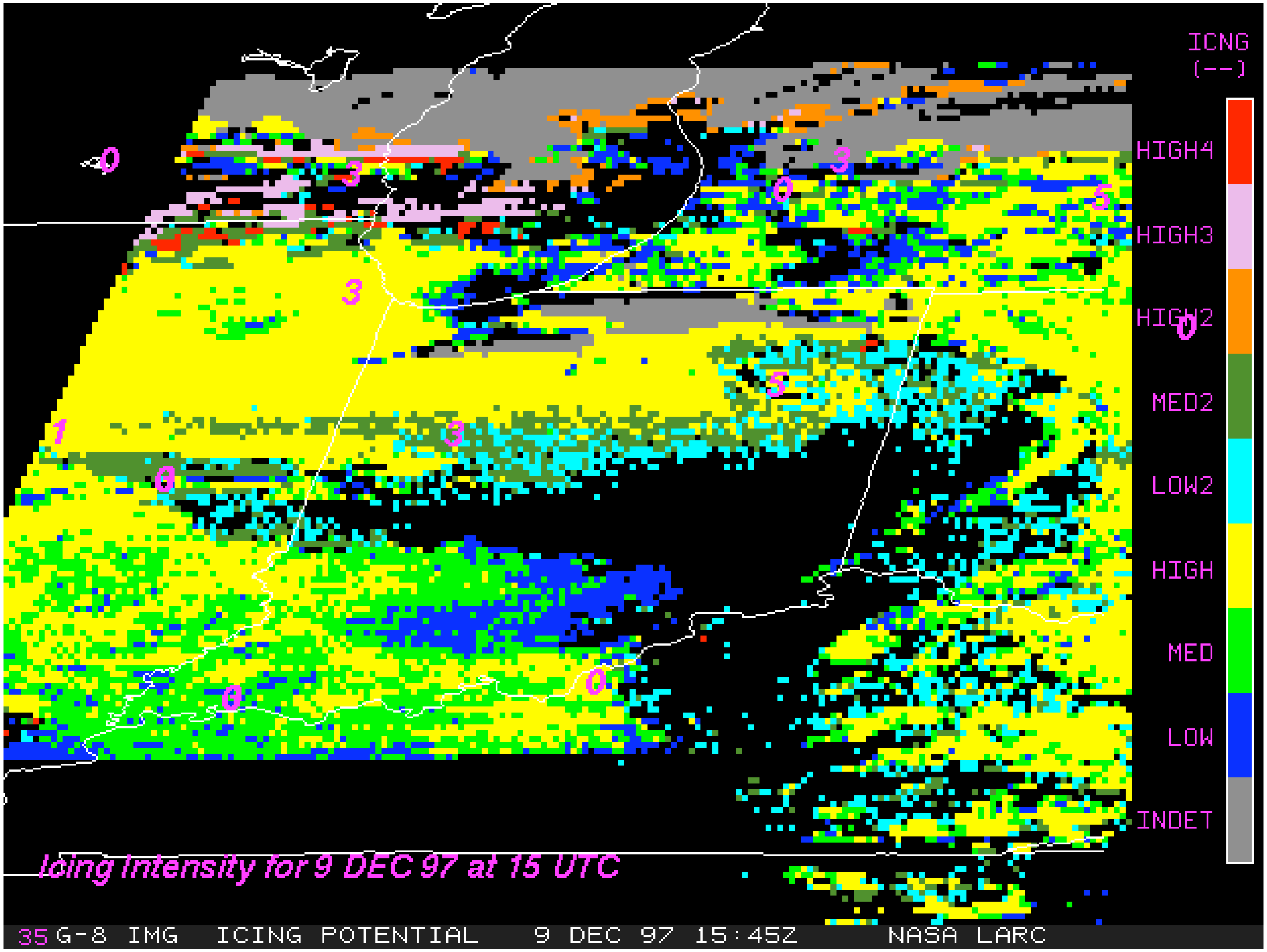
Icing Remote Sensing Meeting, Boulder, CO, September 16-17, 2003

Combined GOES-8 & GOES-10 CONUS Icing Probability PROTOTYPE

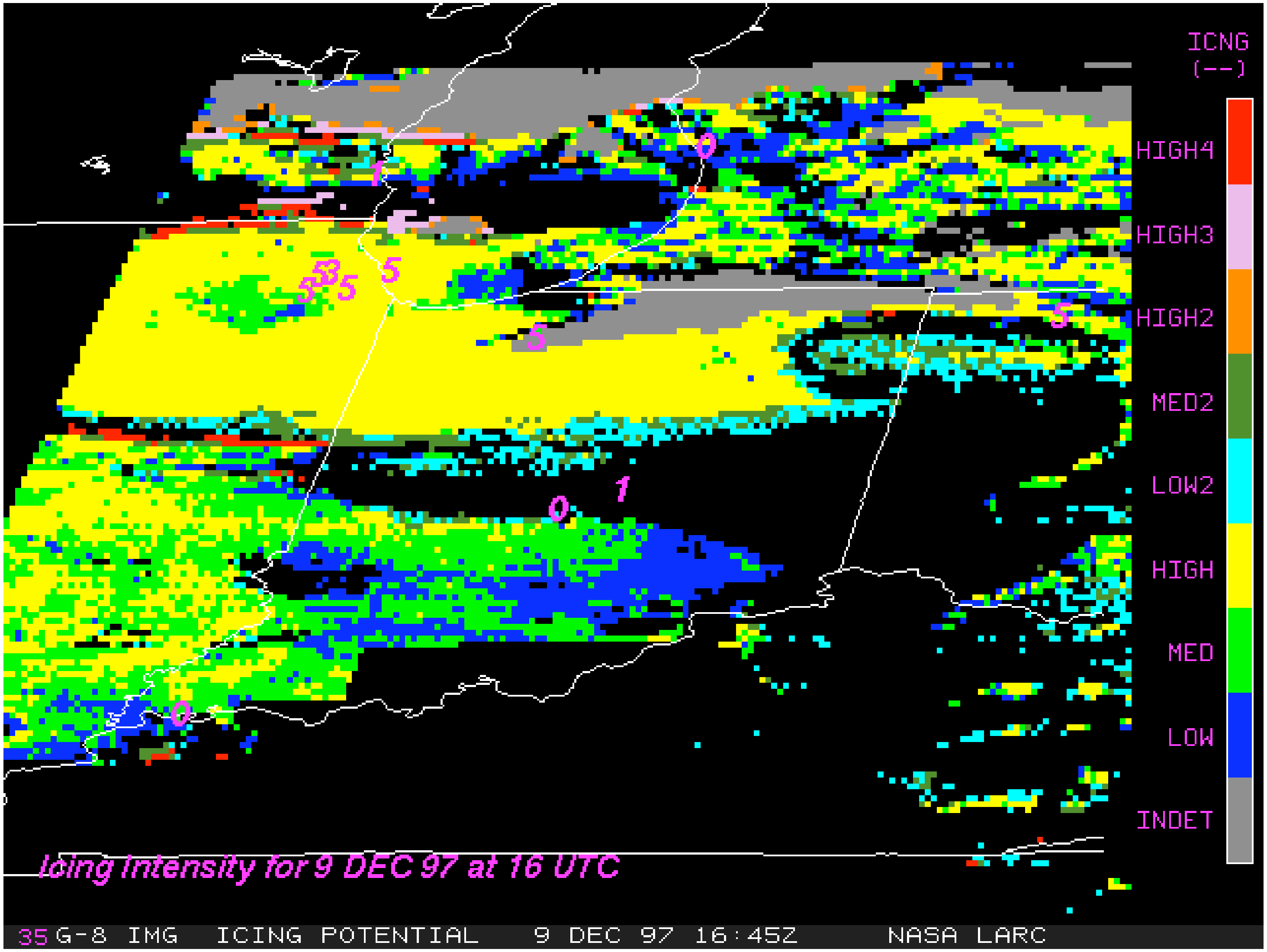
28 January 2003, 1745 UTC



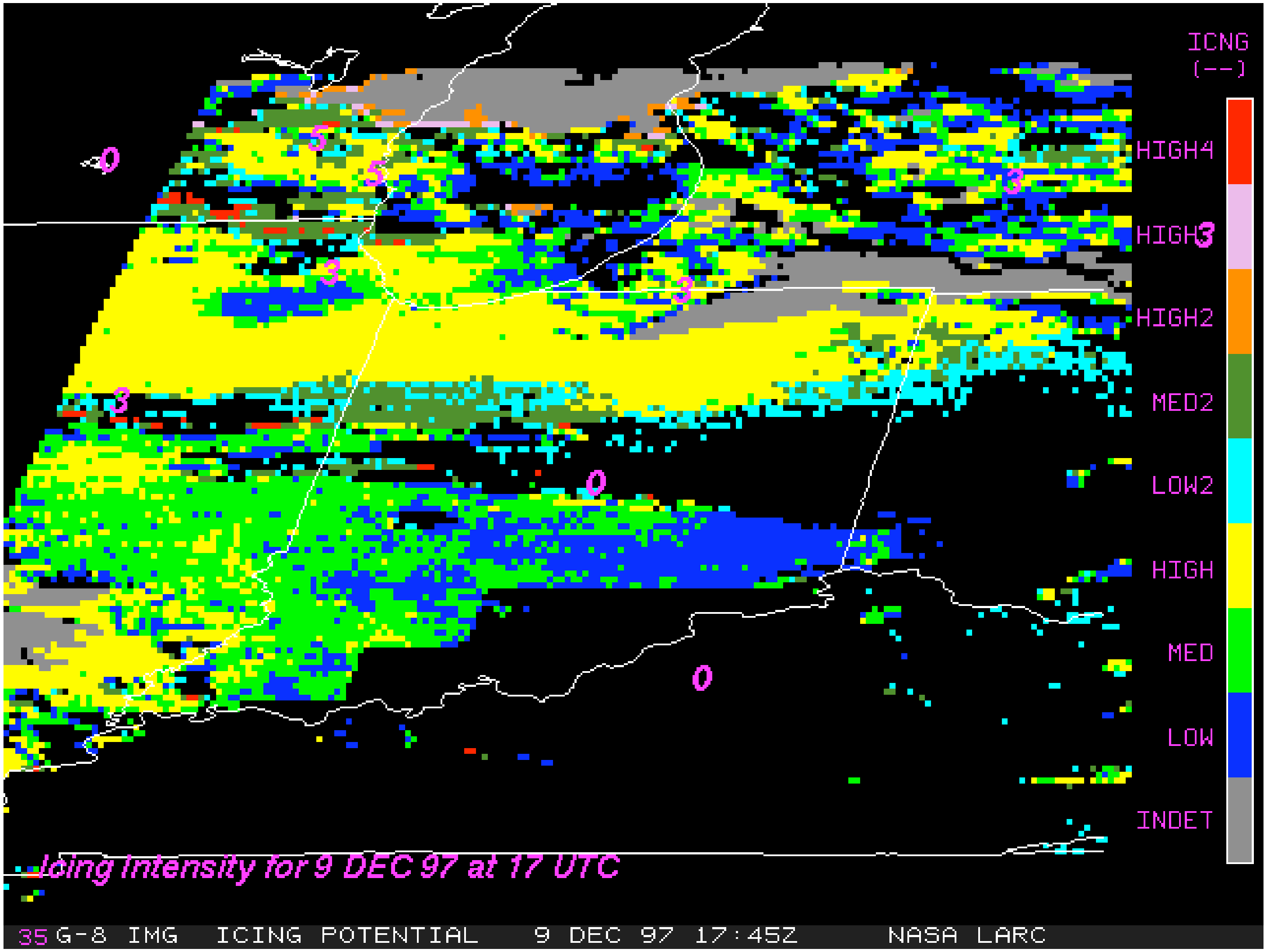
Comparison of Icing Categories With PIREPS, 9 Dec 1997, 1545 UTC



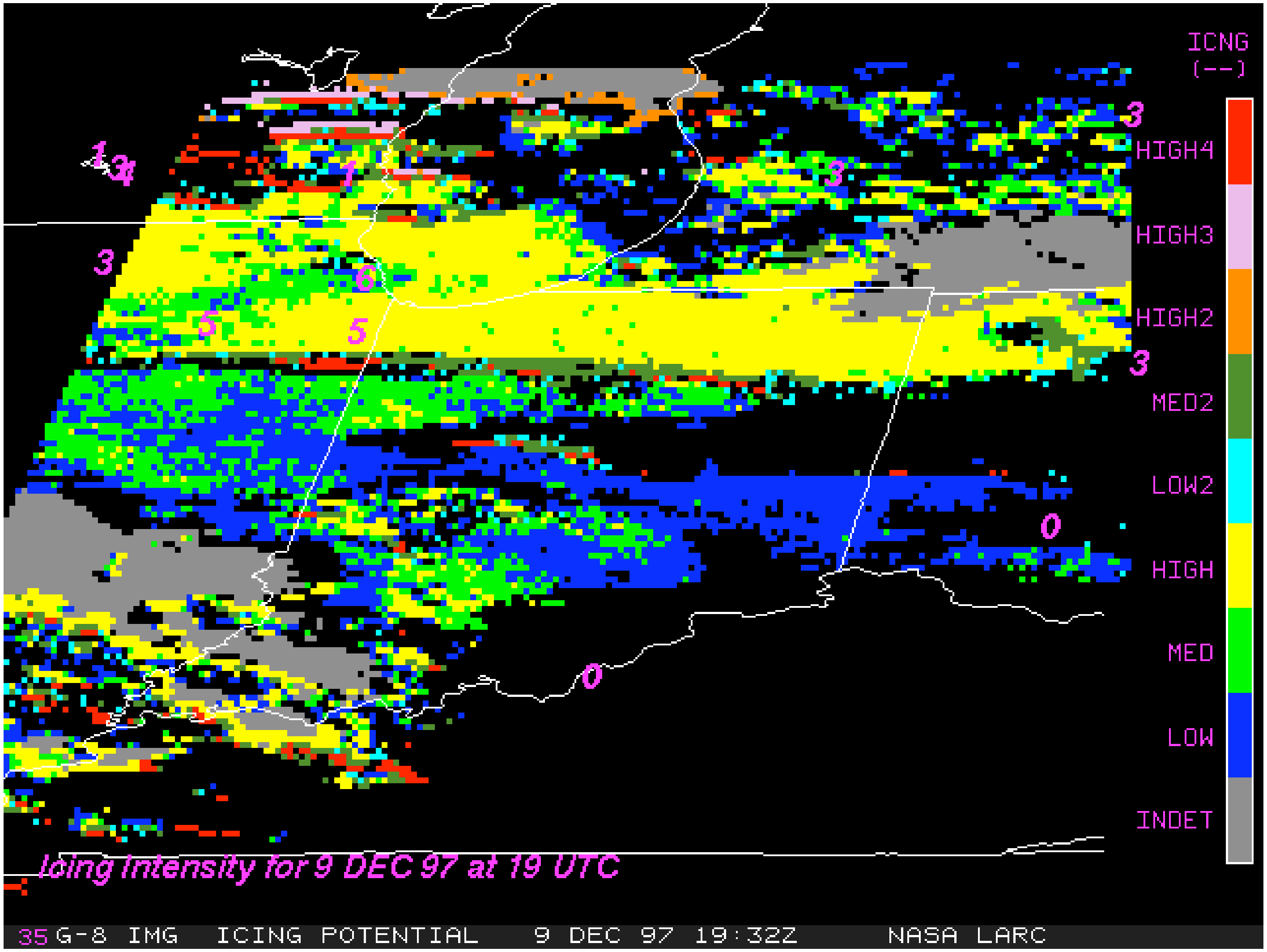
Comparison of Icing Categories With PIREPS, 9 Dec 1997, 1645 UTC



Comparison of Icing Categories With PIREPS, 9 Dec 1997, 1745 UTC



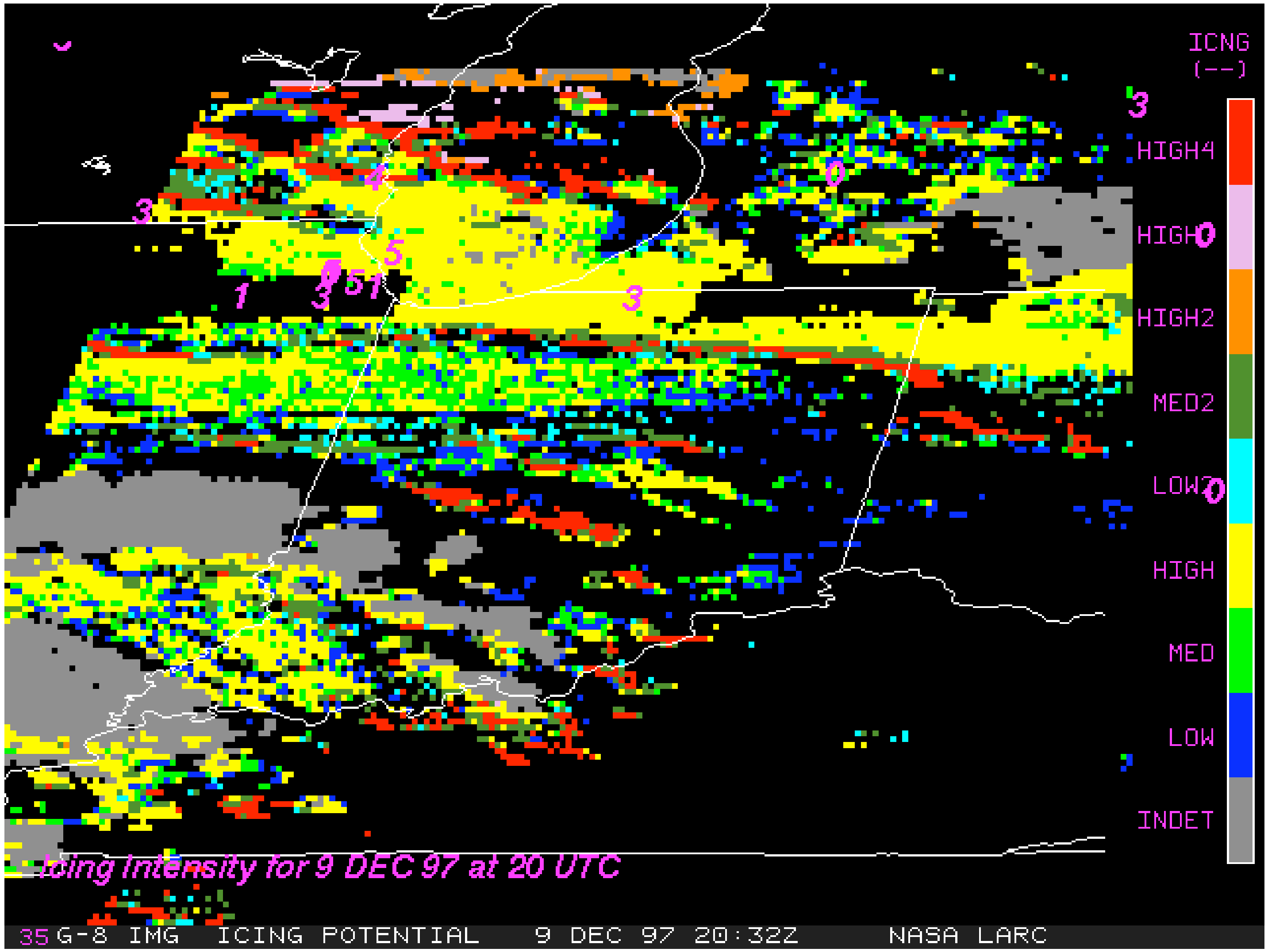
Comparison of Icing Categories With PIREPS, 9 Dec 1997, 1932 UTC



Comparison of Icing Categories With PIREPS, 9 Dec 1997, 2032 UTC

PIREP Icing generally corresponds to yellow (high):

LWP > 300 g/m^2
& re > 11 μm



SUMMARY

• Prototype system has been developed to produce icing products over CONUS every 15-30 minutes during daytime

- icing intensity
- cloud-top & base heights

• Initial validations appear promising

- Much additional aircraft, radar, and model verification needed

AIRS and other future & previous experiments

CHALLENGES TO BE ADDRESSED

- **Icing definition (probability, intensity)**

    - objective definition, relate satellite parameters to icing

- **Daytime validation, algorithm refinement**

    - aircraft & surface measurements, cirrus contamination, input maps, backscatter angle bias, snow background (1.6/3.7 μm), impact of size distribution on retrieval, cloud height/base/vertical slicing

- **Multilayer / high-cloud**

    - what inferences can be made in obscured conditions?

- **Nighttime/twilight algorithm refinement**

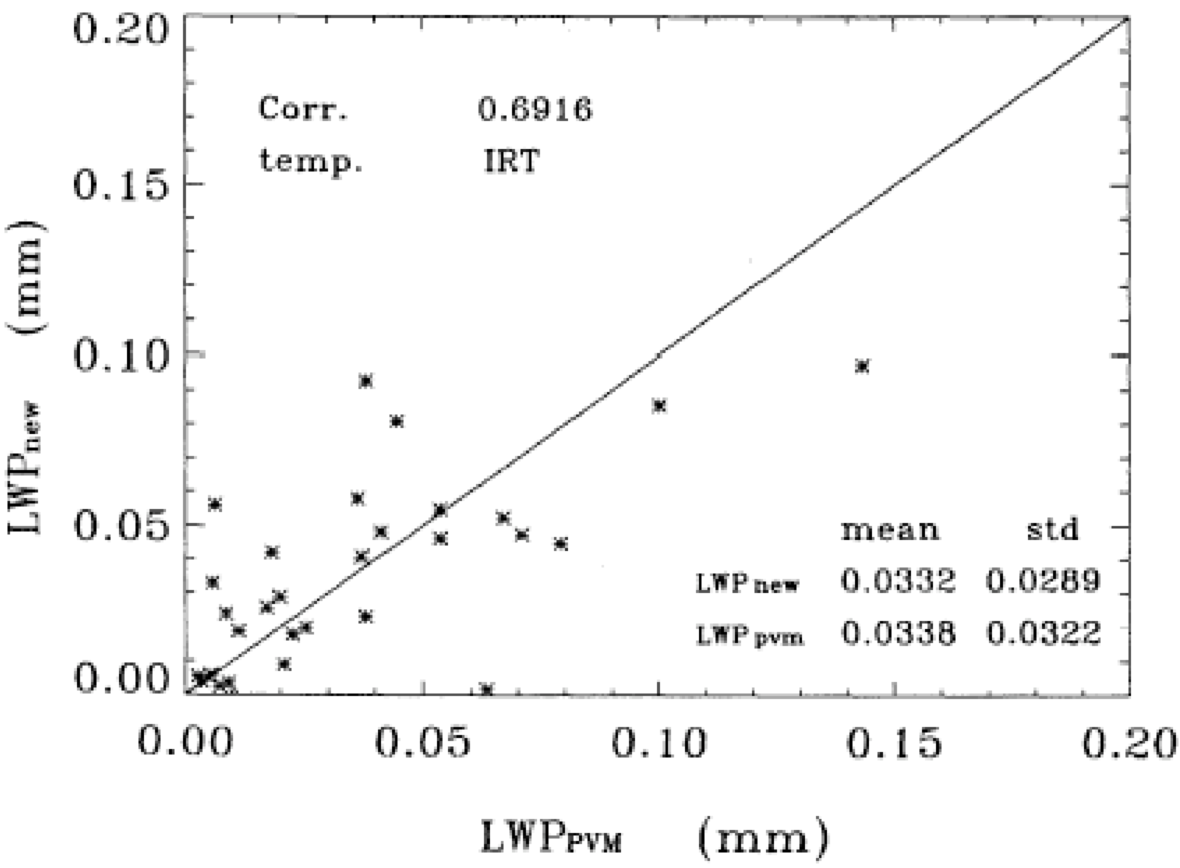
    - how far can we push infrared techniques?

- **Use of microwave data (DMSP, TRMM, AMSR) for ocean (single and multilayer)**

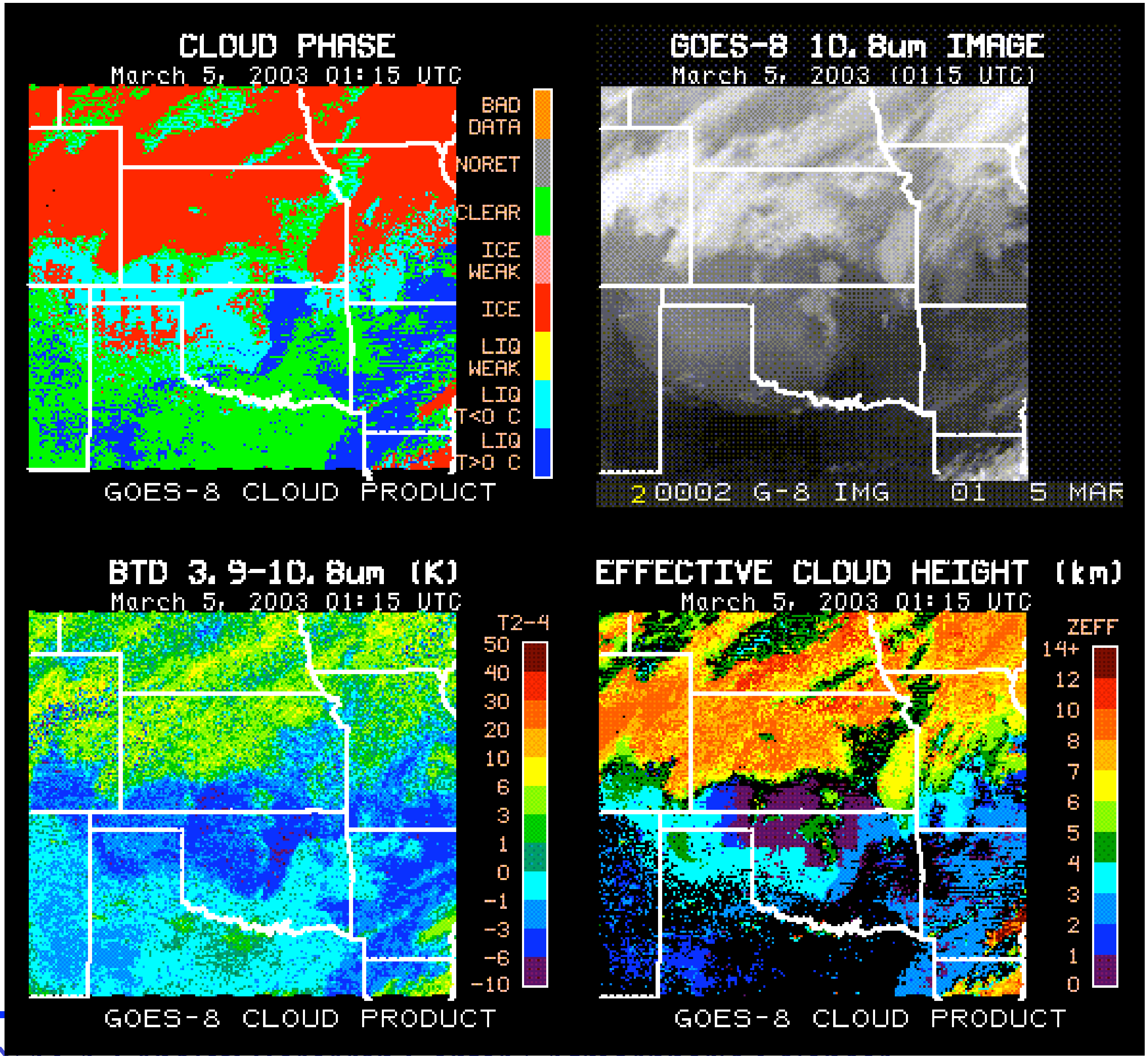
- **Integration of satellite results into comprehensive, operational icing product**

COMPARISON OF IN SITU & MWR (Lin) LWP, FIRE ACE 2000

Can apply microwave method over ocean to retrieve LWP & Tcld in both obscured (ice cloud) & unobscured conditions (DMSP, AMSR data)



Nighttime Analyses over Central USA March 5, 2003



LINKS

- **Main homepage: www-pm.larc.nasa.gov**
- **R/T Imagery: www-angler.larc.nasa.gov/armsgp/g8usa.html**
- **R/T Products**
  - **ARM SGP: www-angler.larc.nasa.gov/armsgp/cldprod4.html**
  - **Midwest USA: www-angler.larc.nasa.gov/armsgp/ cldprod4ohio.html**
  - **Florida: www-angler.larc.nasa.gov/crystal/ cldprod4.html**
  - **CONUS Icing: under development, prelim results on main homepage-Icing link**

- Patrick Minnis: **p.minnis@nasa.gov**
- Bill Smith: **william.l.smith@nasa.gov**